NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

Simulation and Analysis of a MFQPSK Signal
Transmitted Through an Acoustic Medium

by

Anita S. Daniel

December 1989

Thesis Advisor: Paul H. Moose

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REPORT DOCUMENTATION PAGE

REPORT SECURITY CLASSIFICATION Unclassified	1b RESTRICTIVE MARKINGS
SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT
DECLASSIFICATION/DOWNGRADING SCHEDULE	Approved for public release; distribution is unlimited.
PERFORMING ORGANIZATION REPORT NUMBER(S)	5 MONITORING ORGANIZATION REPORT NUMBER(S)
NAME OF PERFORMING ORGANIZATION Naval Postgraduate School; 6b OFFICE SYMBOL *(If Applicable)* 32	7a NAME OF MONITORING ORGANIZATION Naval Postgraduate School
ADDRESS *(City, State, and ZIP Code)* Monterey, CA 93943-5000	7b ADDRESS *(City, State, and ZIP Code)* Monterey, CA 93943-5000
NAME OF FUNDING/SPONSORING ORGANIZATION; 8b OFFICE SYMBOL *(If Applicable)*	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
ADDRESS *(City, State, and ZIP Code)*	10 SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO. / ROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

TITLE *(Include Security Classification)* Simulation and Analysis of a MFQPSK Signal Transmitted Through an Acoustic Medium

PERSONAL AUTHOR(S) ANITA S. DANIEL

TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT *(Year, Month,Day)*	15 PAGE COUNT
Master's Thesis	From To	1989 December	171

SUPPLEMENTARY NOTATION The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

COSATI CODES			18 SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
ELD	GROUP	SUB-GROUP	Communications, simulation, multi-frequency modulation

ABSTRACT *(Continue on reverse if necessary and identify by block numbeer)*

A multi-frequency quadrature phase shift keyed (MFQPSK) signal has been developed at NPS to be used in computer-to-computer communications. This report discusses the simulation of a MFQPSK signal transmitted from a moving transmitter platform through a near vertical acoustic channel as seen by a moored receiver. The simulated signal is tested against MFQPSK signal theory. The simulation was developed to be an experimental tool for testing various Doppler, synchronization, and coding algorithms/techniques for a MFQPSK communication signal. The degradation of output signal-to-noise ratio due to Doppler shifts caused by the moving transmitter is analyzed. An algorithm for estimating Doppler compression/expansion in the received signal is evaluated.

DISTRIBUTION/AVAILABILITY OF ABSTRACT [X] UNCLASSIFIED/UNLIMITED [ ] SAME AS RPT. [ ] DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION Unclassified
NAME OF RESPONSIBLE INDIVIDUAL Paul H. Moose	22b TELEPHONE *(Include Area code)* (408) 646-2838; 22c OFFICE SYMBOL Code 62ME

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Simulation and Analysis of a MFQPSK Signal Transmitted Through an Acoustic Medium

by

Anita S. Daniel
B.S., Northern Arizona University, 1983

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING SCIENCE

from the

NAVAL POSTGRADUATE SCHOOL
December 1989

ABSTRACT

A multi-frequency quadrature phase shift keyed (MFQPSK) signal has been developed at NPS to be used in computer-to-computer communications.

This report discusses the simulation of a MFQPSK signal transmitted from a moving transmitter platform through a near vertical acoustic channel as seen by a moored receiver. The simulated received signal is tested against MFQPSK signal theory. The simulation was developed to be an experimental tool for testing various Doppler, synchronization, and coding algorithms/ techniques for a MFQPSK communication signal. The degradation of output signal-to-noise ratio due to Doppler shifts caused by the moving transmitter is analyzed. An algorithm for estimating Doppler compression/expansion in the received signal is evaluated.

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I. INTRODUCTION

Data links used in many modern military communication systems require computer-to-computer communications which transmit bits from one terminal to another with a low error rate. The communication channel may be a lowpass channel, if the transmission medium is wire or optical fiber, or a bandpass channel, if the transmission medium is radio frequency (RF) link or acoustic channel. The signal used to carry the data bits must be a properly modulated signal with sufficient energy. It must also be positioned in the frequency spectrum to propagate effectively through the intended medium. Multi-Frequency Modulation (MFM) is a signal modulation format that is readily adaptable to a variety of data link scenarios. MFM does not require special purpose MODEMS to translate between the digital and analog domains and can emulate most existing signal modulation formats as well as generate entirely new formats. MFM's descriptive language is that of Digital Signal Processing (DSP) [Ref. 1]. Simulation and analysis of a Naval Postgraduate School (NPS)-developed MFM signal received through a bandpass channel is the subject of this thesis.

A. BACKGROUND

Classical modulation methods for bandpass channels use amplitude and/or phase to carry signal information on a carrier wave in the channel. When the information source is a finite alphabet, as with data or quantized analog sources such as digitized speech or video, then only a finite number of signal

states are needed to represent or code the source. Phase shift keying (PSK) is an efficient method for coding these signal states or message [Ref 2].

MFM is a modulation technique that is ideally suited for computer-to-computer data transmission and reception because its basic structure is one of time and frequency slots. In MFM, the signals are directly encoded, modulated, decoded, and demodulated using DSP techniques within the host computer. In MFM, signal "packets" located in a given frequency spectrum and time are created as shown in Figure 1. Figure 1 shows a single signal packet. Each packet consists of L bauds of K tones. The length of a baud is ΔT seconds during which K discrete tones are transmitted. The phase of each tone is the coded information. These LK subsignals form an orthogonal signal set. Each subsignal may be independently modulated with phase information.

Dr. P. H. Moose at NPS, in conjunction with the Naval Ocean Systems Center (NOSC) in San Diego, has developed Multi-Frequency Quadrature Phase Shift Keying (MFQPSK) signals to be used in high data-rate acoustic burst communications from moving platforms using medium frequency, relatively wideband (25 percent bandwidths) links [Ref. 1, 3]. A simulation of the MFQPSK signal from a moving platform as seen through a bandpass channel was needed to analyze and test various Doppler, synchronization, and coding techniques and/or algorithms before final implementation of the modulation scheme is actually realized. Thus, the subject of this thesis is the simulation and analysis of a MFQPSK signal from a moving platform as seen through a bandpass channel.

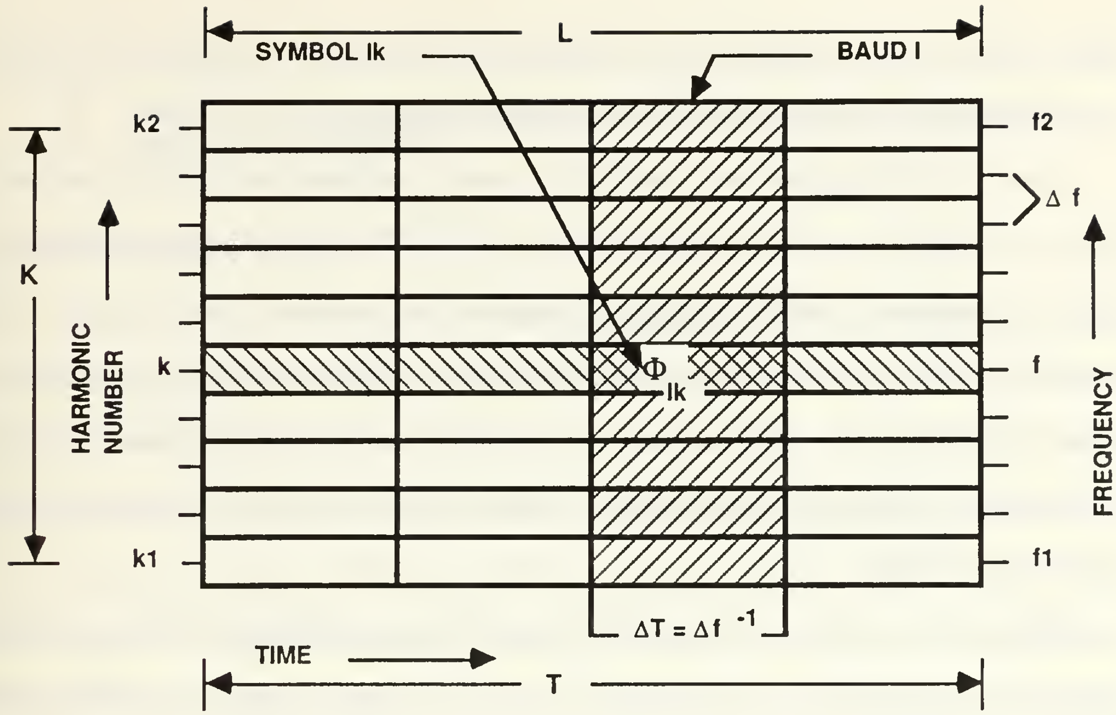


Figure 1. MFM Signal Packet (after Ref. 1: p. 3.)

B. OVERVIEW

The NPS-designed MFQPSK signal will be transmitted from a moving platform. In Chapter II a simple model of the moving transmitter platform's dynamics is developed; its performance is compared to actual track data. This model is implemented in the simulation.

A mathematical description of the transmitted signal and the design parameters of the MFQPSK signal are introduced in Chapter III. The channel parameters which delay and compress/expand this transmitted signal and which characterize the received signal, the additive Gaussian noise which is

added to the received signal after sampling, and the final simulated sampled received signal are derived and presented in Chapter III.

Once the simulation was complete, testing and analysis was performed. First, the simulation was tested against MFQPSK signal theory to insure that the simulated received MFQPSK signal is consistent with theory. The simulated received signal should be consistent with theory so that the simulation may be used as an experimental tool for testing various Doppler, synchronization, and coding algorithms. Chapter IV consists of this analysis and simulation results.

Second, the amount of residual Doppler mismatch which the signal can tolerate due to the moving transmitter was analyzed. Chapter V provides the analysis of the output signal-to-noise ratio degradation due to the Doppler mismatch. Then, in Chapter VI, an estimation of the Doppler compression factor within a baud is derived using the Discrete Fourier Transform of a received signal's baud. The simulated outcome of this estimated Doppler versus the Doppler due to the moving transmitter within a baud is also illustrated in Chapter VI.

In the simulation, the actual Doppler compression/expansion factor due to the dynamics of the moving transmitter is computed; therefore, it is known. The start time of the signal reception is also known; thus, the signal is always perfectly synchronized in the simulation.

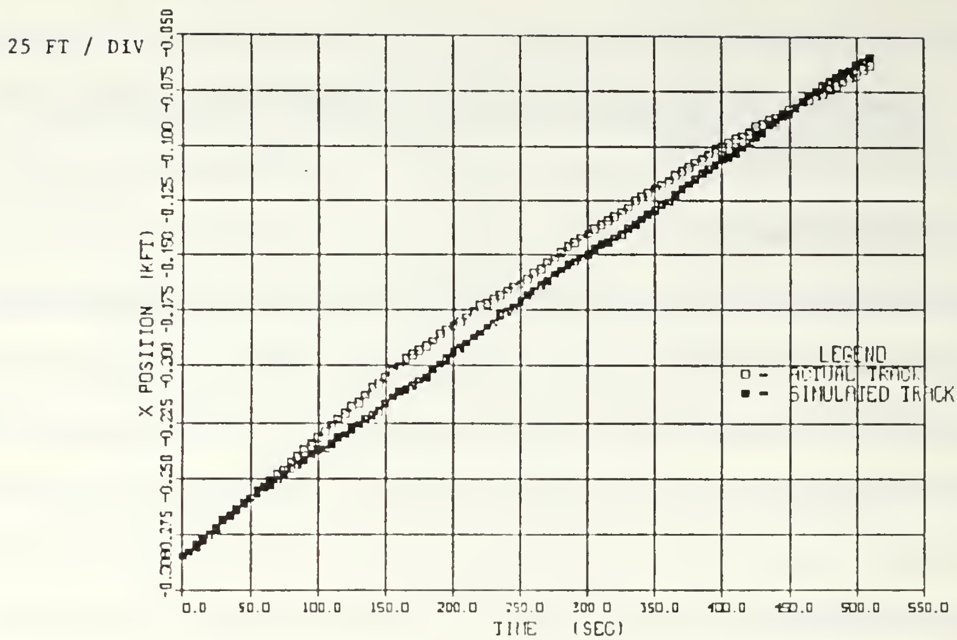
II. MOVING TRANSMITTER PLATFORM DYNAMICS AND BEAM PATTERN

A. BACKGROUND

Since it is assumed that the MFQPSK signal will be transmitted from a moving platform, provision must be made at the receiver to compensate for Doppler shifts. The Doppler shift factor is computed based on the geometry in the simulation using the radial velocity of the moving transmitter relative to the stationary receiver. The complete set of equations for the Doppler shift factor is presented in the next chapter. The radial velocity is the derivative with respect to time of the slant range to the receiver. Realistic slant range values are necessary to compute realistic Doppler shift factors. Slant range is computed using the time-varying x-position, y-position, and z-position of the transmitter relative to the receiver.

B. ACTUAL TRACK DATA VS. SIMULATED TRACK DATA

To realistically model the dynamics of the moving transmitter, actual track data was provided by NOSC. The parameters that were given in the actual track data were x-position, y-position, z-position, and slant range relative to the receiver. A simple random walk model was used to model the track data. This model assumes the transmitter is moving along a straight line with random fluctuations in the x, y, and z velocity components. Figures 2 through 7 illustrate how well the random walk model corresponds to the actual track data on six different runs. The z-position seems to consistently have the largest error. The largest error in the z-position is 25 feet, (see



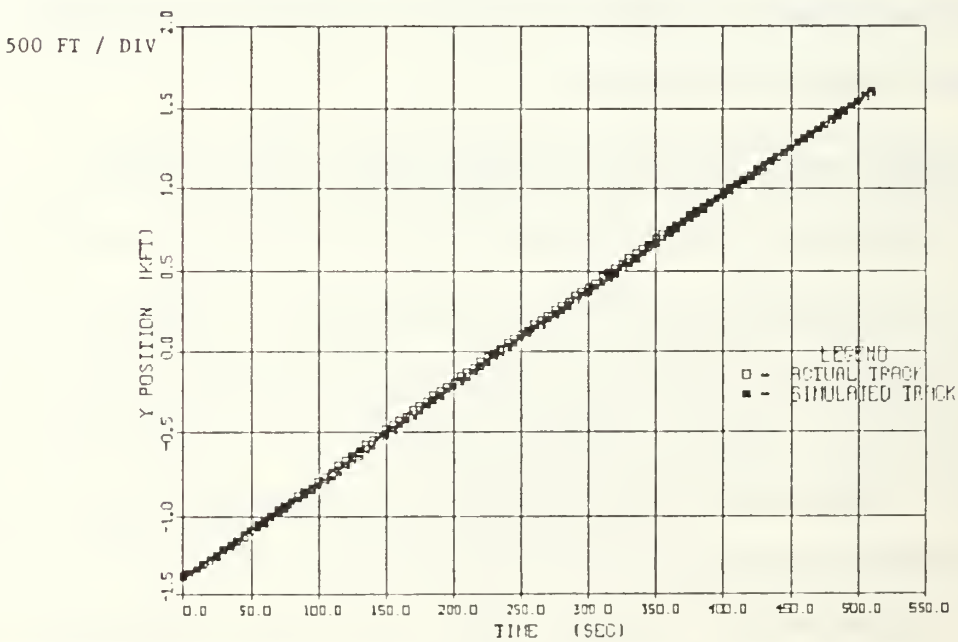
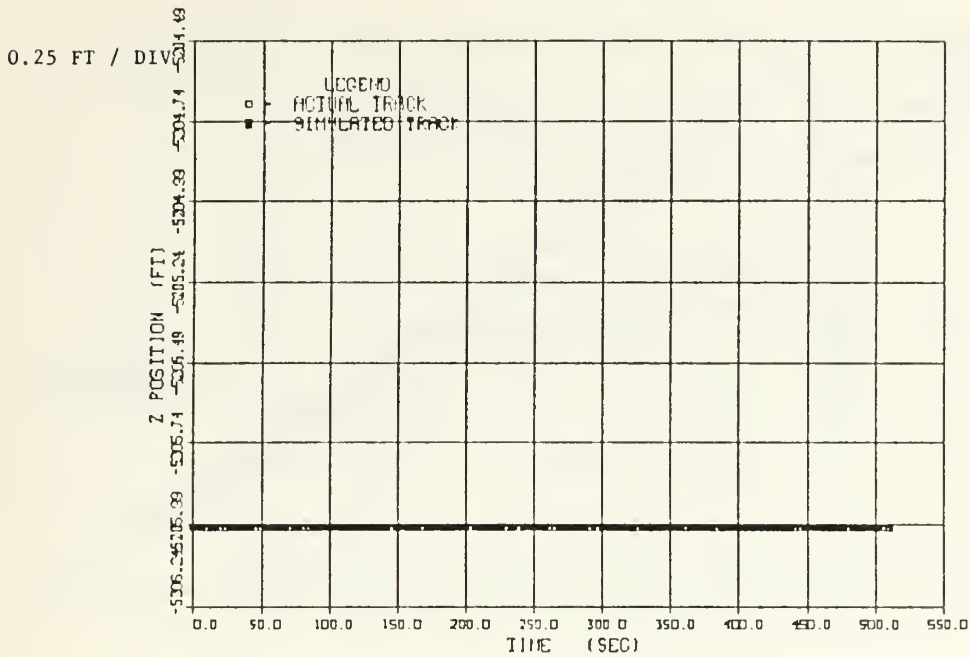


Figure 2a. Run 1: Actual and Simulated Track Data
X–Position and Y–Position vs. Time



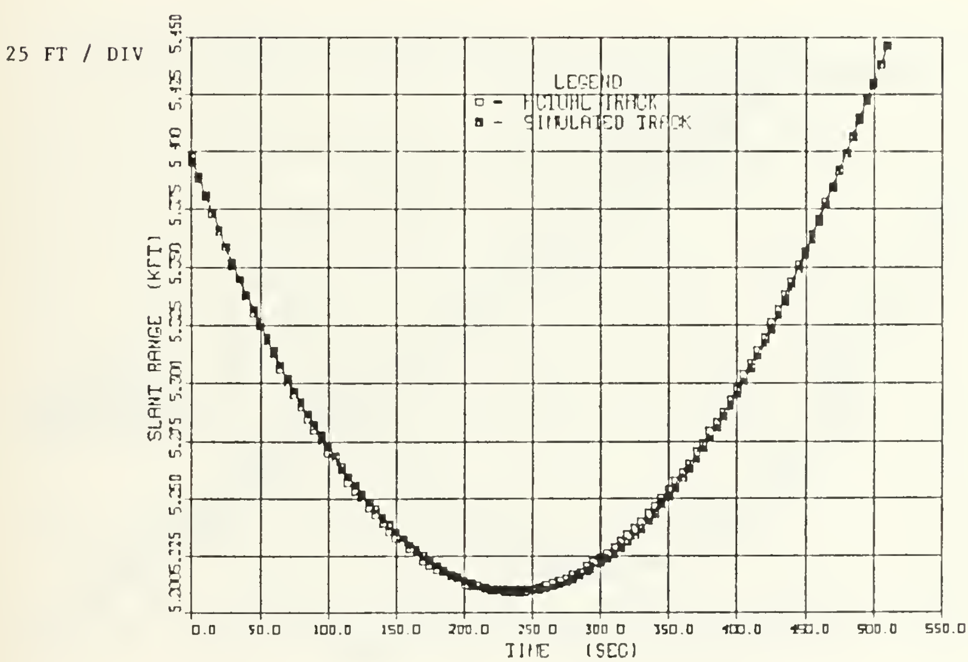
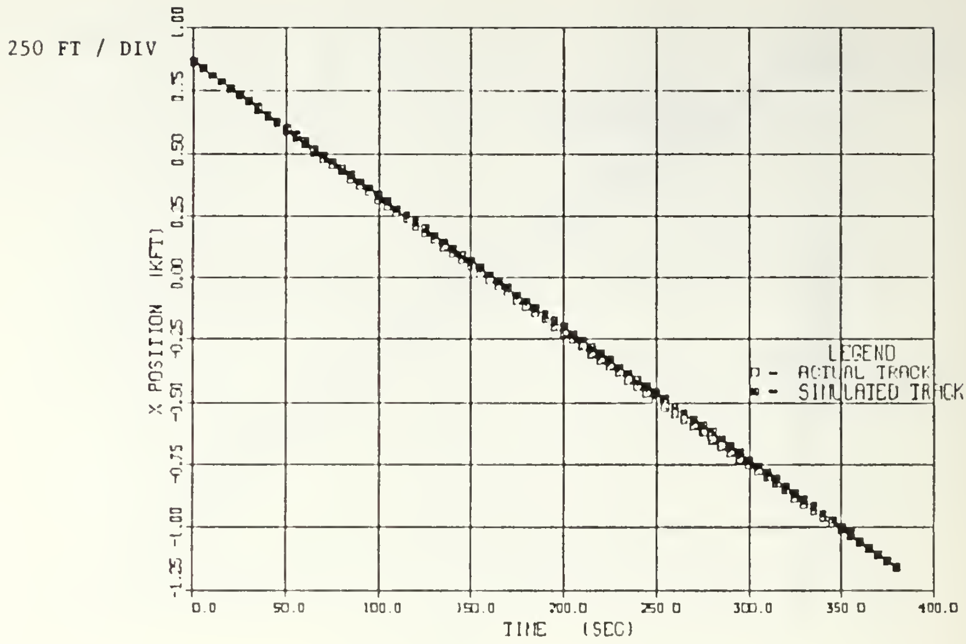


Figure 2b. Run 1: Actual and Simulated Track Data
Z–Position and Slant Range vs. Time



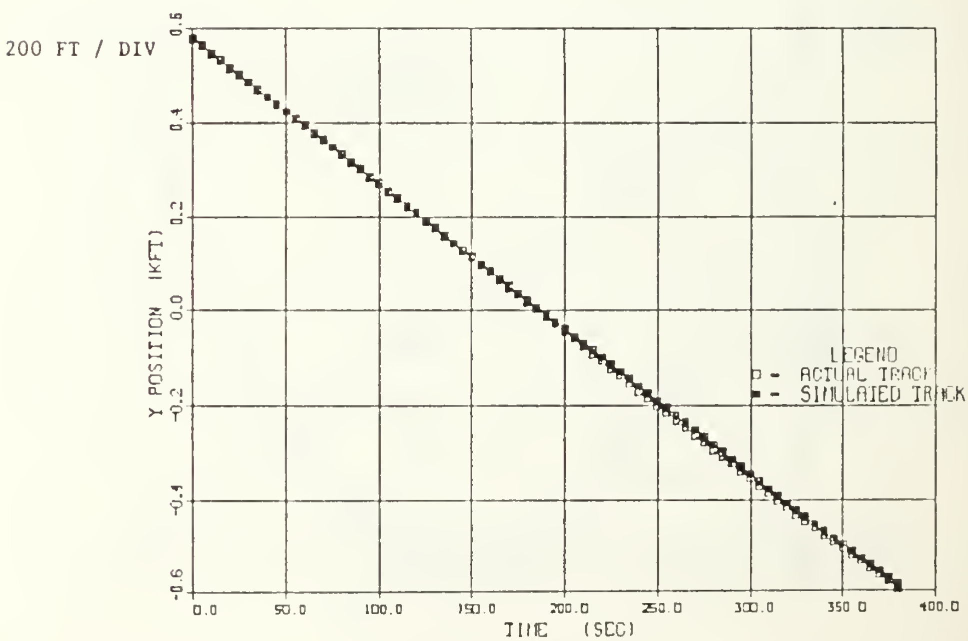


Figure 3a. Run 2: Actual and Simulated Track Data
X–Position and Y–Position vs. Time

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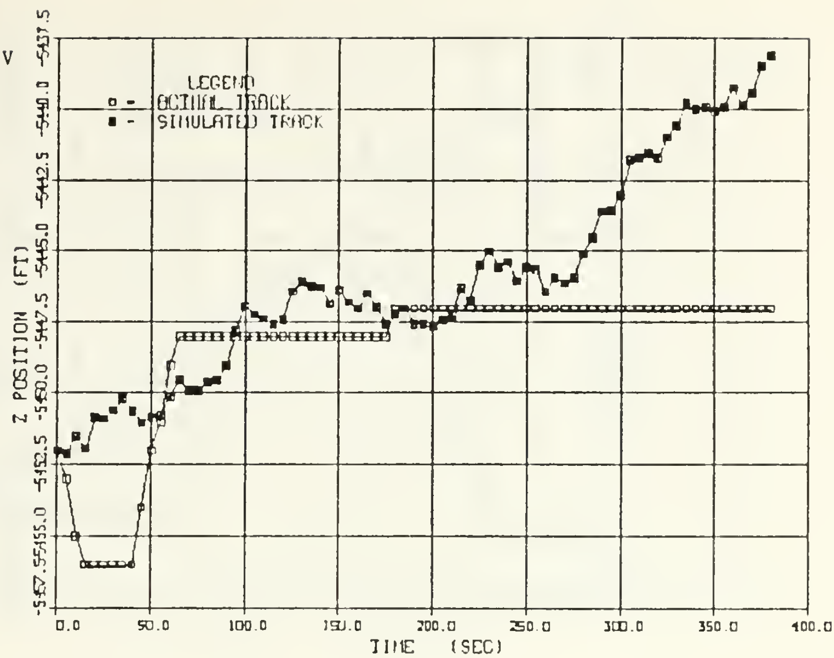

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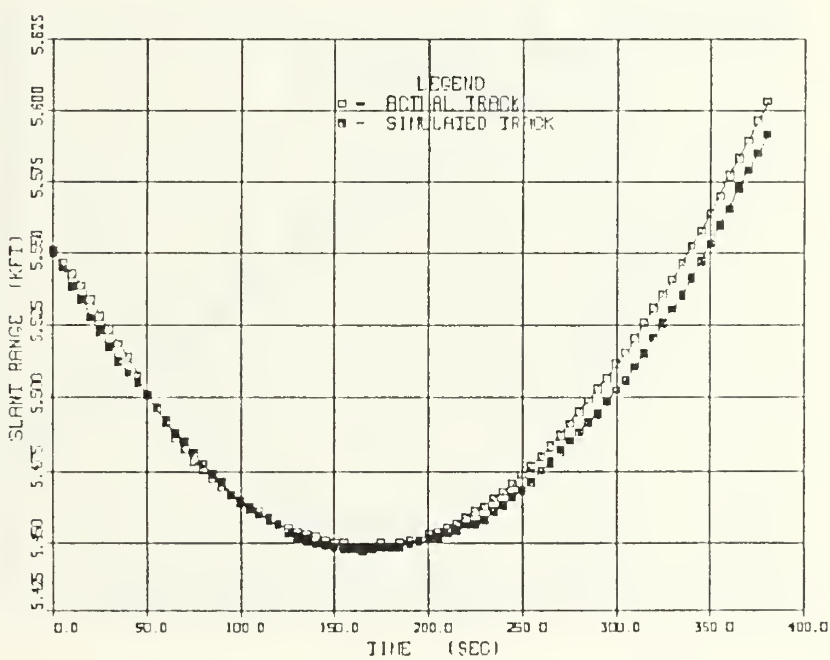
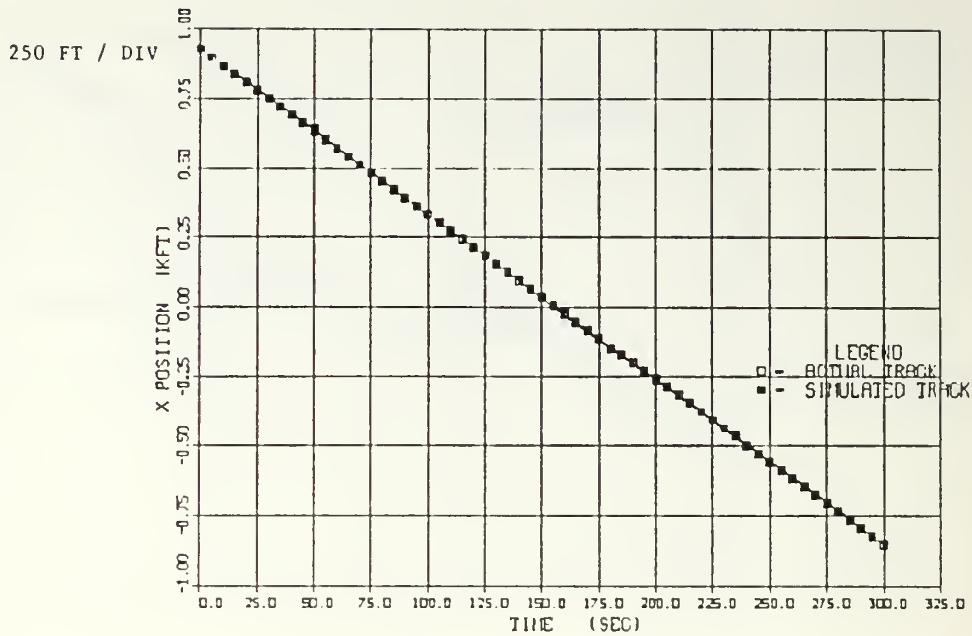


Figure 3b. Run 2: Actual and Simulated Track Data
Z–Position and Slant Range vs. Time



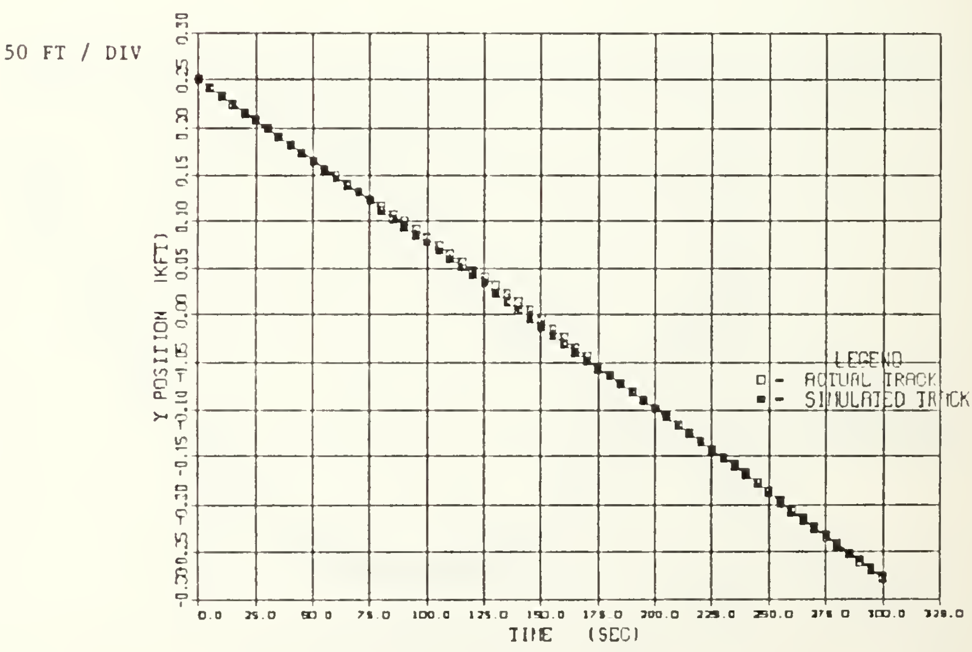
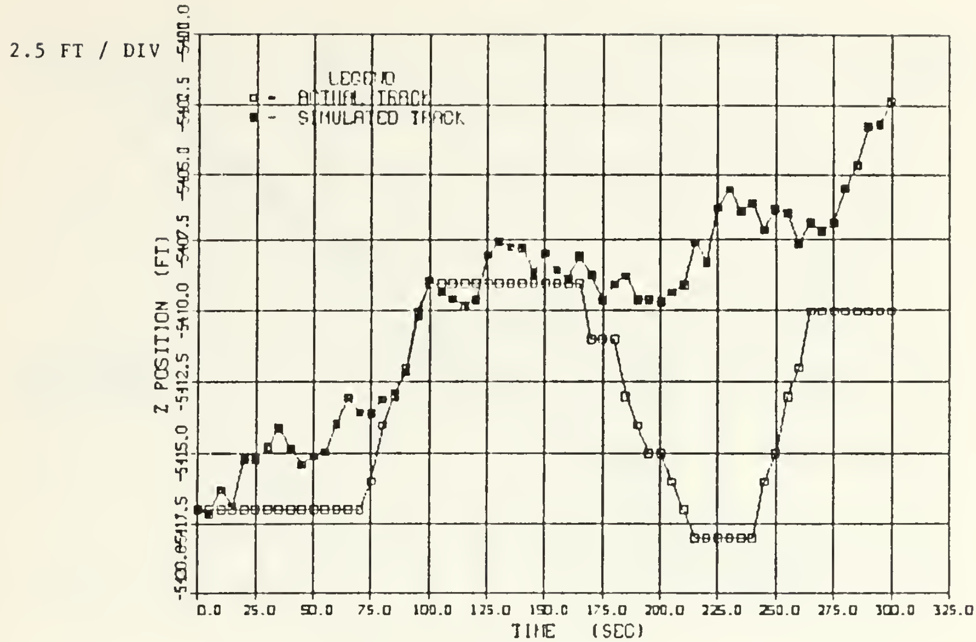


Figure 4a. Run 3: Actual and Simulated Track Data
X–Position and Y–Position vs. Time



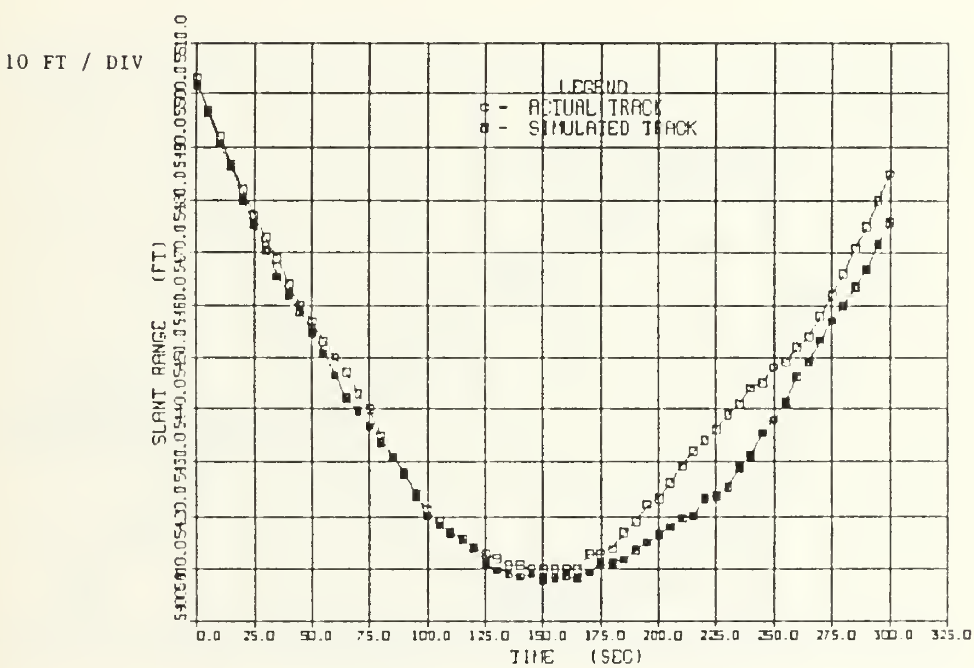
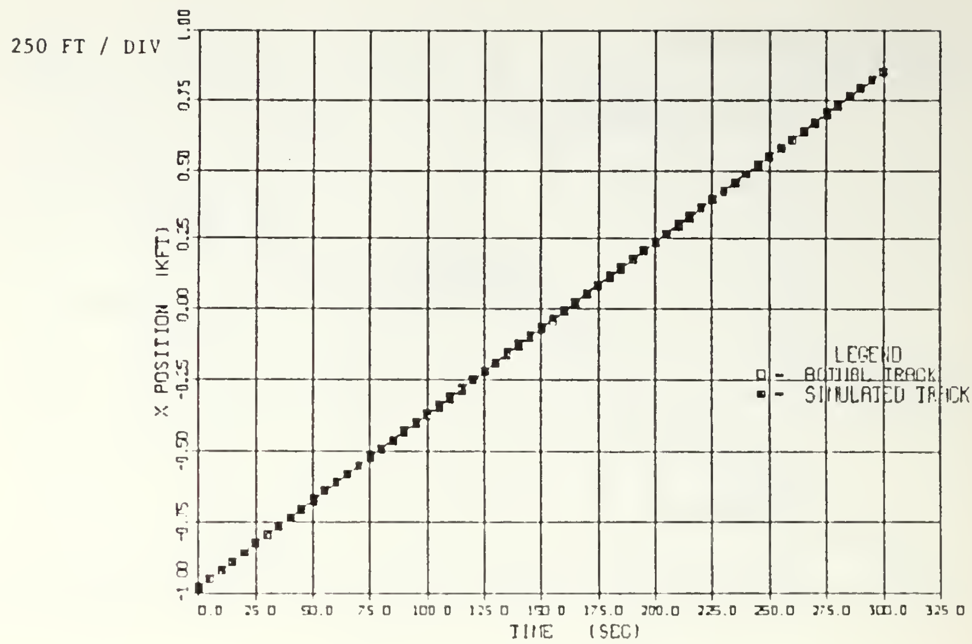


Figure 4b. Run 3: Actual and Simulated Track Data
Z–Position and Slant Range vs. Time



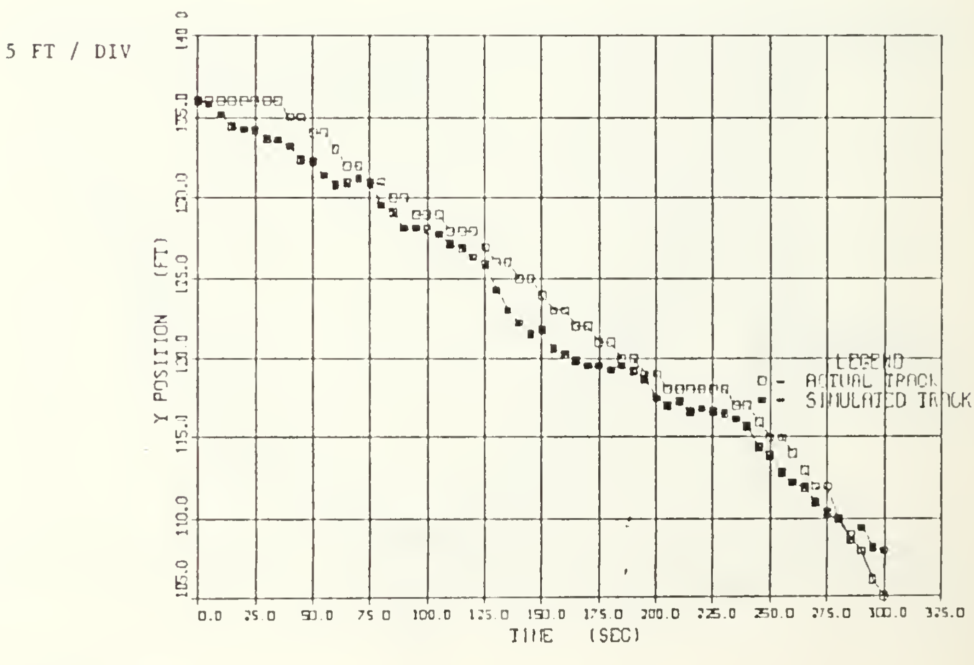
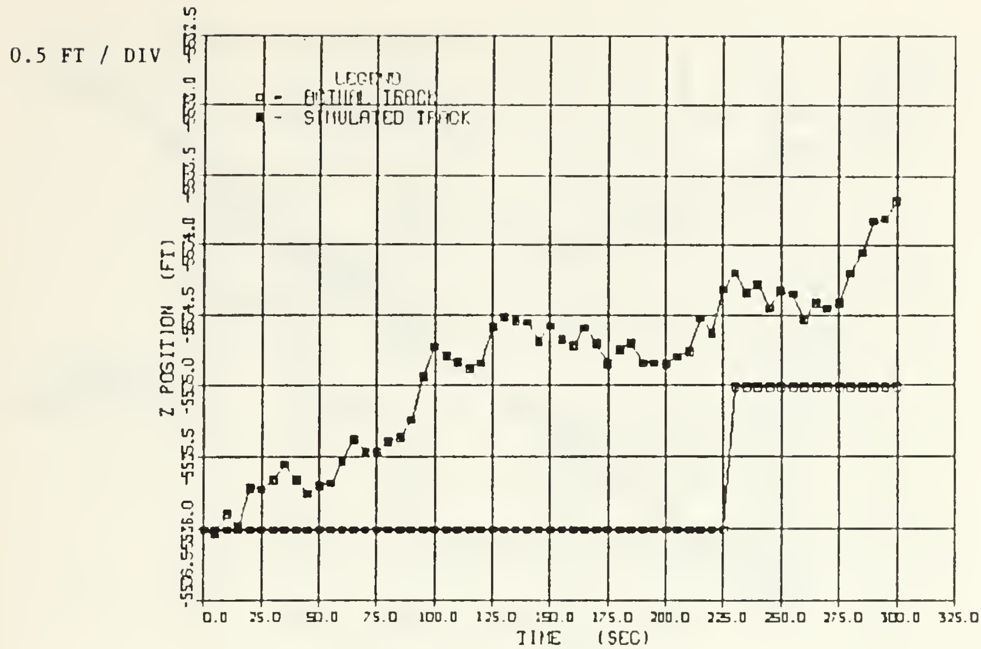


Figure 5a. Run 4: Actual and Simulated Track Data
X–Position and Y–Position vs. Time



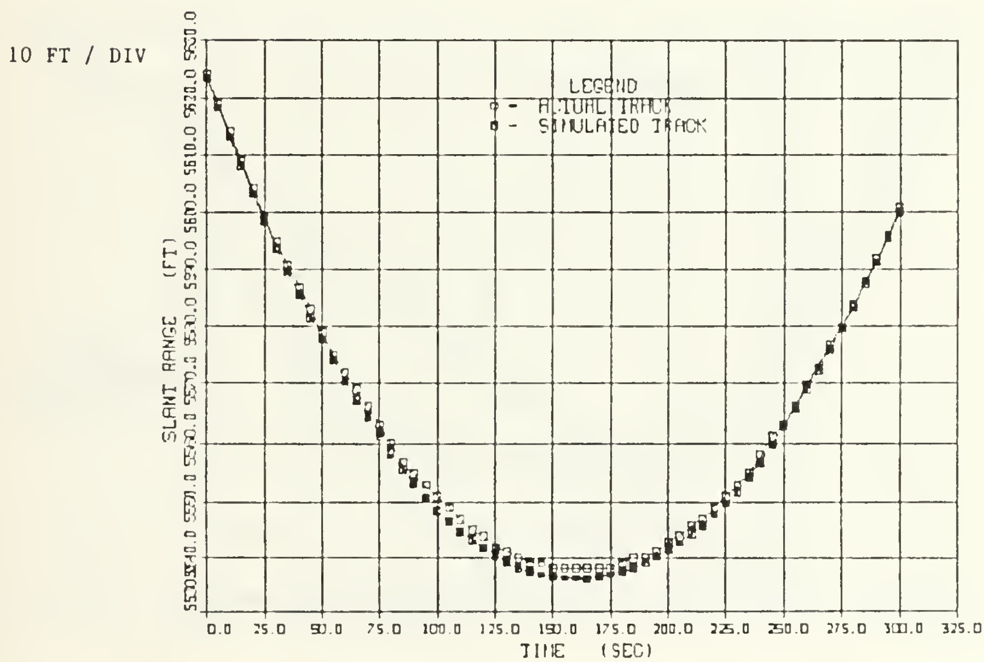
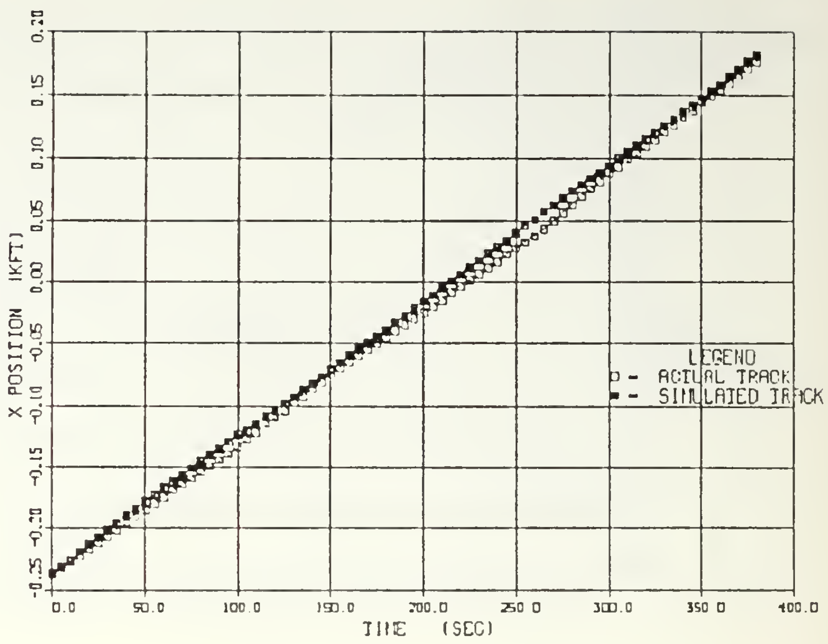


Figure 5b. Run 4: Actual and Simulated Track Data
Z–Position and Slant Range vs. Time

50 FT / DIV



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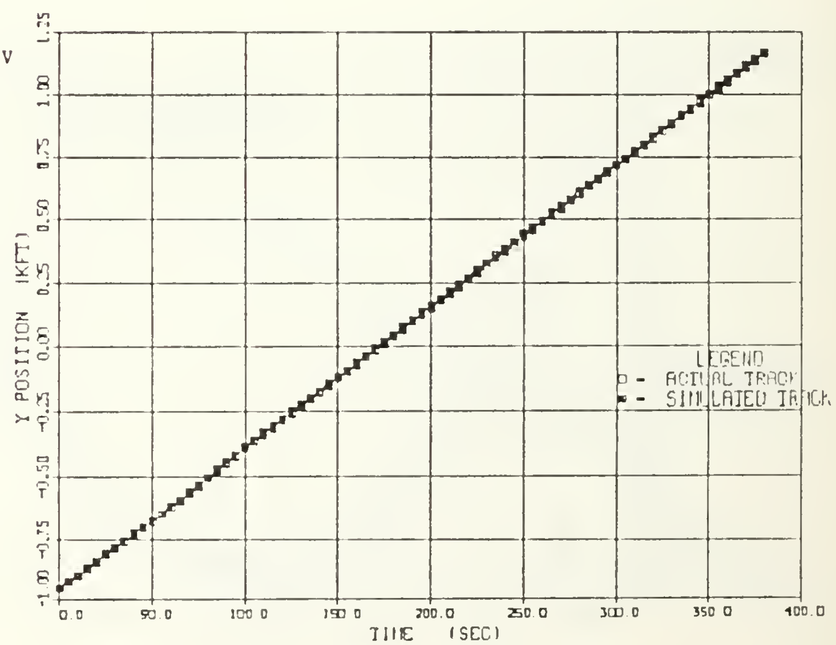
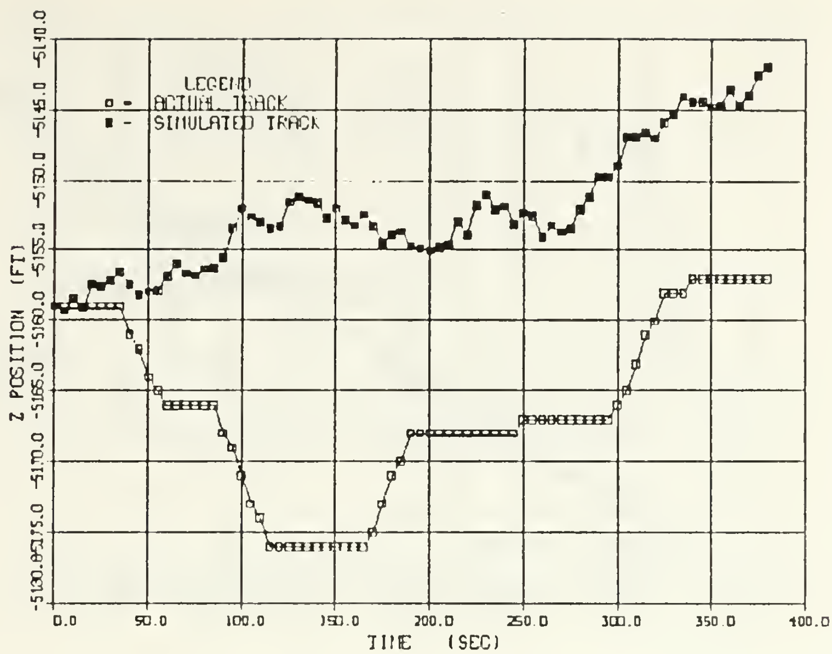


Figure 6a. Run 5: Actual and Simulated Track Data
X–Position and Y–Position vs. Time

5 FT / DIV



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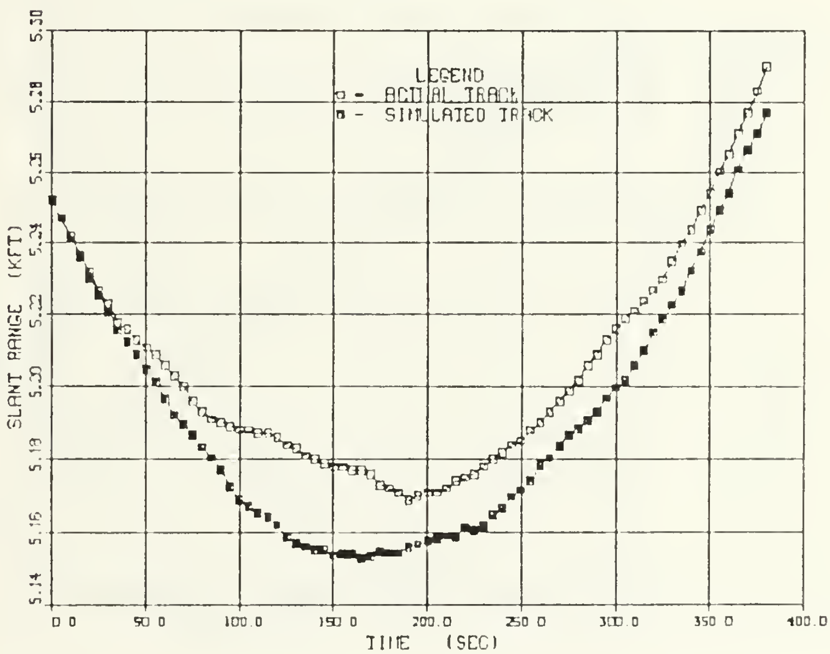
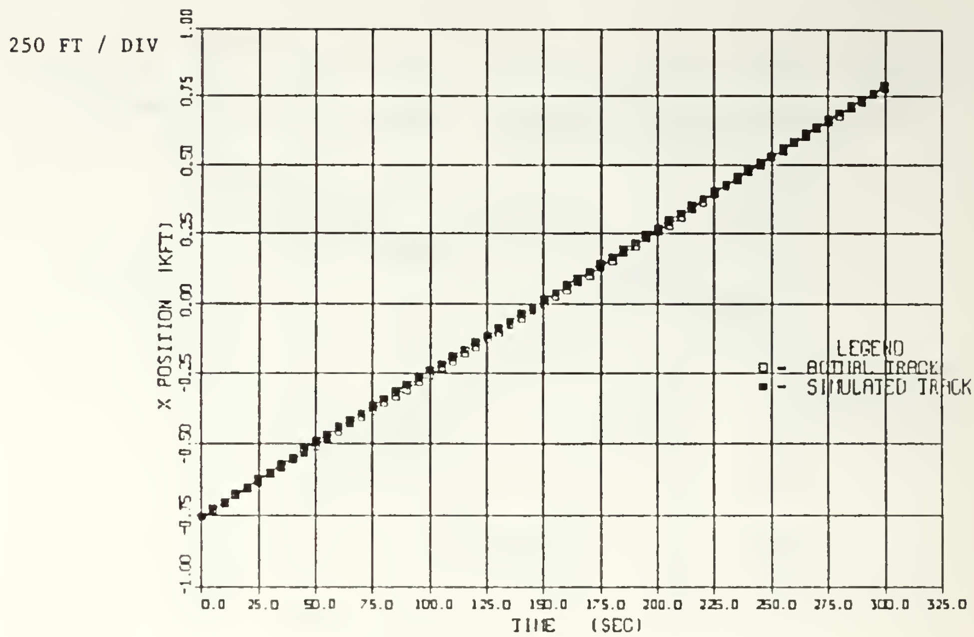


Figure 6b. Run 5: Actual and Simulated Track Data
Z–Position and Slant Range vs. Time



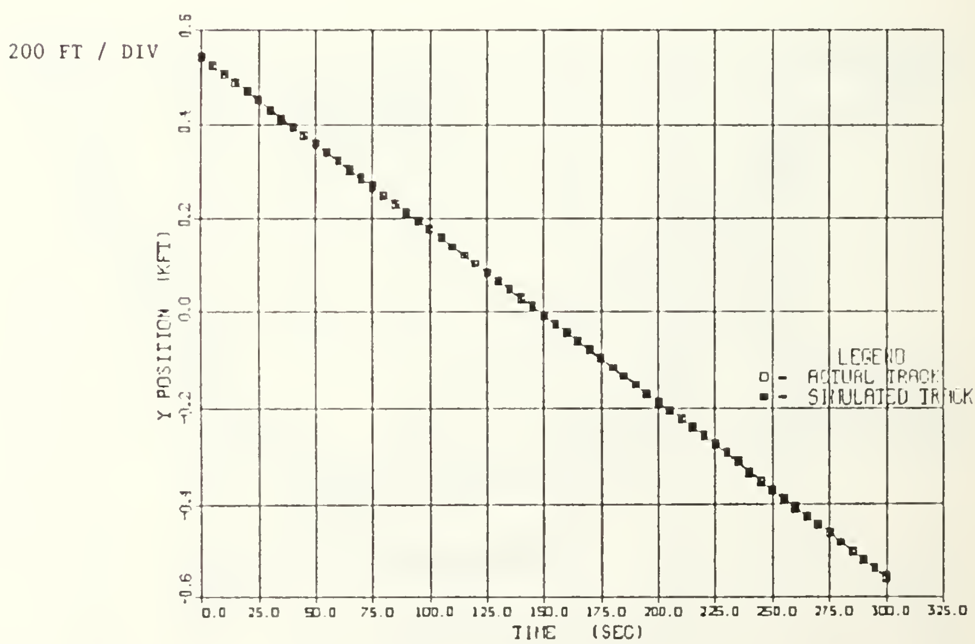
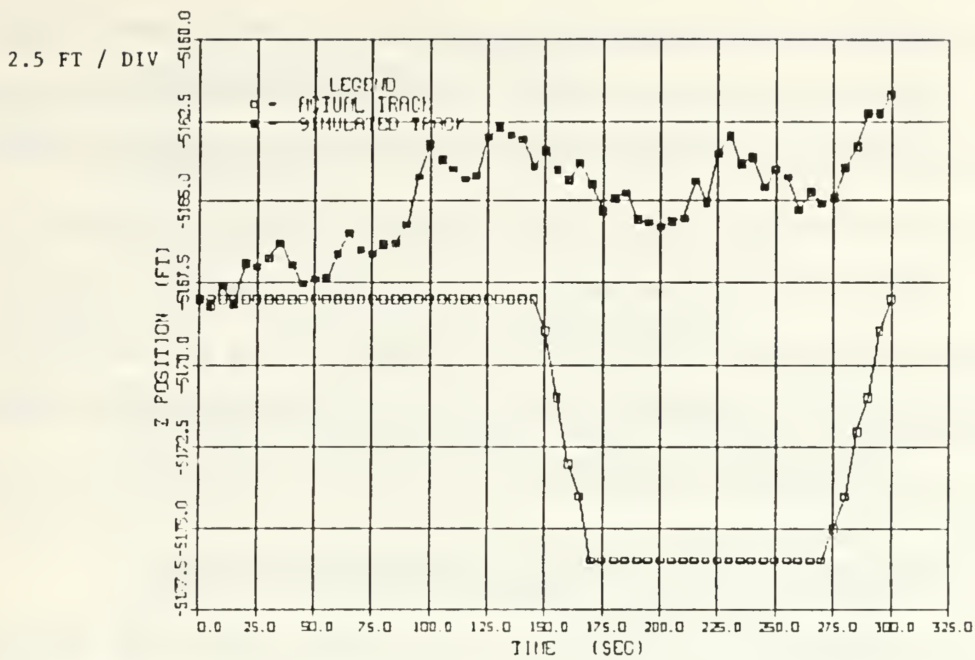


Figure 7a. Run 6: Actual and Simulated Track Data
X–Position and Y–Position vs. Time



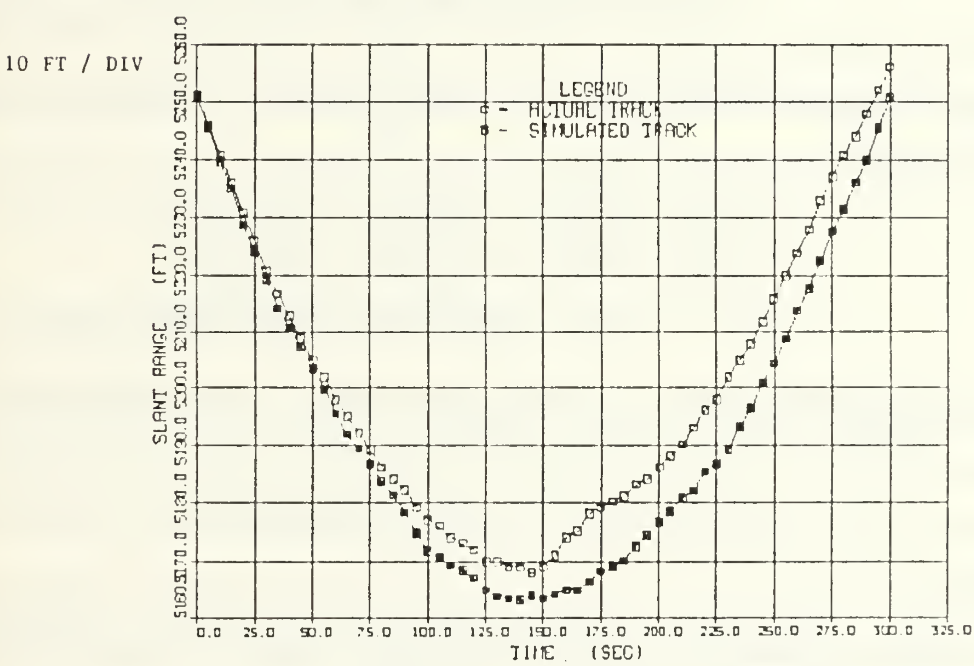


Figure 7b. Run 6: Actual and Simulated Track Data
Z–Position and Slant Range vs. Time

Figure 6b). Note that the z-position graphs have a smaller vertical scale than the x- and y-position graphs. Ideally, since the transmitter is attempting to maintain a constant depth, the location should not fluctuate much in the z direction as was the case in Run 5 shown in Figure 6b. However, overall there is little error for these six runs in the model output for the slant range; therefore, the random walk model was considered to be an adequate model of the transmitter's dynamics for the purpose of simulating Doppler shifts, time delays, and propagation losses of the MFM acoustic communication signal.

C. TRANSMITTER PLATFORM DYNAMICS MODEL

The following three equations are the random walk model used to simulate the transmitter's dynamics. The names of the variables used in the simulation are the same as those used in the equations below. When applicable, the parameters from Figure 1, which are printed in boldface, are equated to their simulation variables, printed in capital letters. The dynamics model is described by:

$$X(LL) = X(LL-1) + (VX(LL) * DELT(LL)) \tag{1}$$

$$Y(LL) = Y(LL-1) + (VY(LL) * DELT(LL)) \tag{2}$$

$$Z(LL) = Z(LL-1) + (VZ(LL) * DELT(LL)) \quad . \tag{3}$$

The slant range to the receiver is computed using the following equation;

$$R(LL) = (X(LL)^2 + Y(LL)^2 + Z(LL)^2)^{0.5} \tag{4}$$

where,

X(LL): The position of the transmitter relative to the receiver in the x direction during the LL^{th} baud

Y(LL): The position of the transmitter relative to the receiver in the y direction during the LL^{th} baud

Z(LL): The position of the transmitter relative to the receiver in the z direction during the LL^{th} baud

R(LL): Slant range of the transmitter relative to the receiver during the LL^{th} baud

LL = l: The baud number of the transmitted signal

DELT(LL) = Δ**T** : The LL^{th} baud length in seconds

VX(LL): The velocity in the x direction during time DELT(LL). VX(LL) is Gaussian distributed with mean = VXAVG and variance = VXVAR. VXAVG and VXVAR are input by the user.

VY(LL): The velocity in the y direction during time DELT(LL). VY(LL) is Gaussian distributed with mean = VYAVG and variance = VYVAR. VYAVG and VYVAR are input by the user.

VZ(LL): The velocity in the z direction during time DELT(LL). VZ(LL) is Gaussian distributed with mean = VZAVG and variance = VZVAR. VXAVG and VXVAR are input by the user.

Note: LL and l are used interchangably throughout.

The rectangular coordinate system of the transmitter's motion is relative to the receiver. The origin (0, 0, 0) is perpendicular to the receiver in the plane of the transmitter (the x-y plane) as shown in Figure 8.

D. TRANSMITTER BEAM PATTERN

If the receiver is not within the transmitter's transmission beam, then the message will not be received. The simulation does not use the actual beam pattern of the transmitter; therefore, it does not know if the receiver is within the beam pattern. The simulation assumes the receiver is within the transmitter's beam the entire time of transmission (i.e., from the beginning of the first signal packet to the end of the last signal packet).

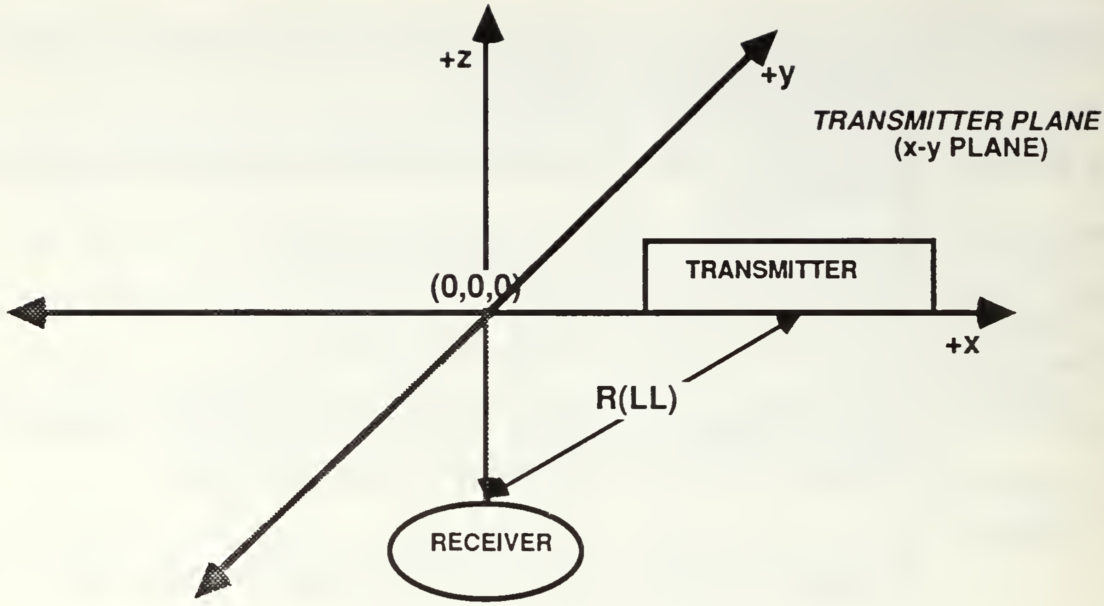


Figure 8. Coordinate System of the Transmitter and Receiver

The angle between the transmitter's slant range and z-position relative to the receiver is computed and output graphically by the simulation. This angle, THETAD(LL) in the simulation, is

$$\text{THETAD(LL)} = \arccos(\ \text{abs(Z(LL))} / \text{R(LL)}\ ) * (180.0 / \text{PI}) \tag{5}$$

where PI = 3.141592654. Figure 9 illustrates the geometry of the line of sight angle, THETAD(LL) = θ, and THETA0 = θ_0, the half beam width of the transmission beam.

The simulation user can graphically observe the value of THETAD(LL) for each baud and determine for a given THETA0 if the receiver would actually be able to receive the transmitted signal. The simulation does not

stop if THETAD(LL) is greater than the input half beam width of the transmitter, THETA0, but a warning message is output to the screen. The initial position (X0, Y0, Z0) and THETA0 are inputs to the simulation.

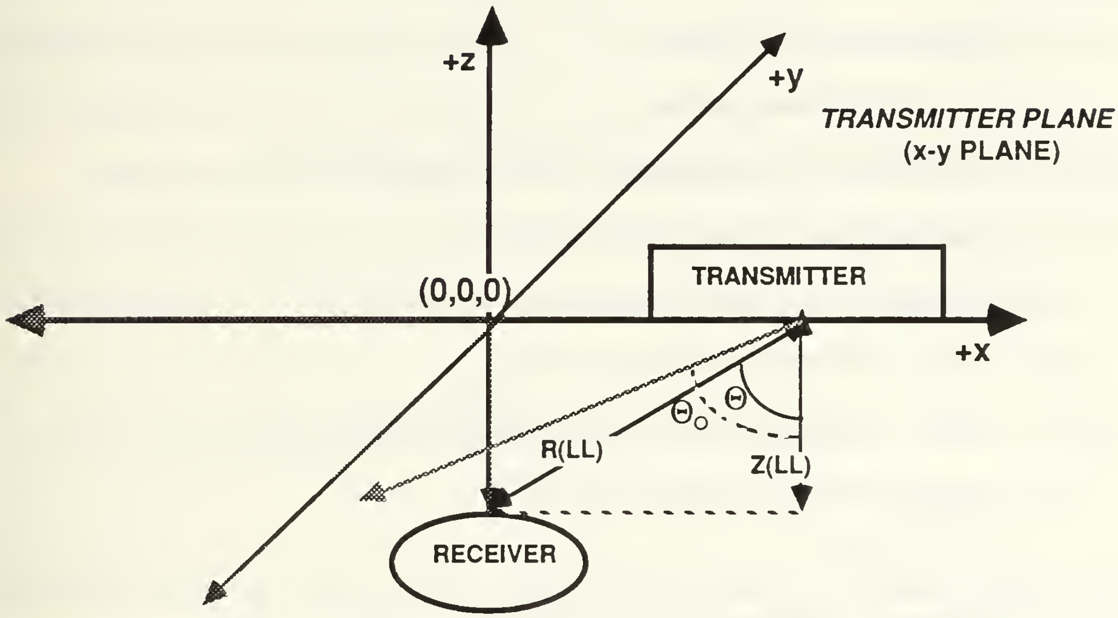


Figure 9. Geometry of the Transmission Beam

III. DERIVATION OF THE SIMULATED RECEIVED MFQPSK SIGNAL

A. DESCRIPTION OF THE TRANSMITTED MFQPSK SIGNAL

Referring to Figure 1, the following definitions are used in MFQPSK [Ref. 1]:

T : Packet length in seconds

ΔT : Baud length in seconds

k_x : Baud length in number of samples (not in Figure 1)

L : Number of bauds per signal packet

Δt : Time between samples in seconds

$f_x = 1 / \Delta t$: Sampling frequency in Hz

$\Delta f = 1 / \Delta T$: Minimum frequency spacing between MFM tones in Hz

K : Number of MFM tones in a baud

l : Baud number

k : Harmonic number of the MFM tone

Φ_{lk} : Symbol or phase on the k^{th} tone of the l^{th} baud

Since $\Delta t = \Delta T / k_x$, the sampling frequency is $f_x = k_x * \Delta f$. Consequently there are a maximum of $k_x/2$ tones spaced Δf Hz apart in frequency covering the range from 0 Hz to $f_x/2$ Hz. Here $f_x/2$ is the Nyquist frequency [Ref. 2]. The K tones carry the phase information during each baud. The relationship between f_i, the i^{th} frequency, and k_i, the i^{th} harmonic, is $k_i = f_i / \Delta f$. Some of the tones may not be used (i.e., their amplitudes are set equal to zero) during any or all bauds of the packet. To generate the transmitted bandpass signals

between frequencies f_1 and f_2, only tones between harmonics $k_1 = f_1 / \Delta f$, the minimum harmonic number or tone, and $k_2 = f_2 / \Delta f$, the maximum tone, will be given non-zero amplitudes. The harmonic numbers less than k_1 and greater than k_2 are given zero amplitudes. The number of tones in a baud is $K = k_2 - k_1 + 1$. These K contiguous tones are transmitted with non-zero amplitudes. The signal bandwidth is $W = K * \Delta f$. Thus, the time bandwidth product of the entire signal packet is $TW = L * \Delta T * \Delta f * K = LK$, which is the total number of symbols that can be sent in one signal packet.

A mathematical description of the transmitted MFQPSK signal is necessary to understand some of the parameters used to simulate the received MFQPSK signal. The l^{th} baud of the transmitted signal is described by:

$$x_l(u) = \sum_{k=k_1}^{k_2} x_{lk}(u) \quad ; \quad 0 \le u \le \Delta T \tag{6}$$

where $x_{lk}(u) = A_{lk} \cos(2\pi\, k\, \Delta f\, u + \Phi_{lk})$ [Ref. 1]. Here, u is time referenced to the beginning of the baud. Actual real time is $t = t_o + (l*\Delta T) + u$ where t_o is the time at the beginning of the 0^{th} baud (i.e., the beginning time of the first signal packet).

The discrete time signal corresponding to the l^{th} baud is generated by sampling (6) at the sampling intervals $\Delta t = 1/f_x$. Thus, the discrete time signal is given by:

$$x_l(n) = \sum_{k=k_1}^{k_2} x_{lk}(n) \quad ; \quad 0 \le n \le (k_x - 1) \tag{7}$$

where $x_{lk}(n) = A_{lk} \cos((2\pi\ k\ n) / k_x + \Phi_{lk})$. Here, n is discrete time referenced to the beginning of the baud.

Note that a baud interval of time ΔT seconds contains *exactly* k cycles of tone k. Therefore, adjacent tones differ by one in the number of cycles they generate during a baud.

The phase, Φ_{lk}, may be given one of the four values $\pi/4$, $3\pi/4$, $-3\pi/4$, or $-\pi/4$, which are in quadrants 1 through 4 respectively. These four values make up the symbol set used to code the information or message on the signal. The simulation variable for Φ_{lk} is PHI(LL,K).

The design parameters used in the MFQPSK signal designed and developed by Dr. P. H. Moose at NPS are listed in Table I. These parameters are for a signal packet in a 16 to 20 KHz bandpass channel. These parameters are also used in the simulation to uniquely characterize a chosen baud type (i.e., baud types 1 through 5). The simulation variables in capital letters are equated to the parameters they represent. Recall that LL = l, the baud number.

B. TIME DELAY AND COMPRESSION/EXPANSION OF THE TRANSMITTED SIGNAL

When the MFQPSK signal is transmitted, there are various factors which can affect the signal such as a moving transmitter, the channel or the medium, and the receiver. In the simulation, these parameters are computed and applied to the transmitted signal, thus producing a model of the received signal baud. By delaying and compressing/expanding the signal in time, the frequencies of the transmittedsignal are shifted in the received signal. Some

TABLE I

DESIGN PARAMETERS FOR SIGNAL PACKET IN A 16-20KHZ BANDPASS CHANNEL

BAUD TYPE:	1	2	3	4	5
ΔT = DELT(LL) (sec)	1/240	1/120	1/60	1/30	1/15
Δf = DELF(LL) (Hz)	240	120	60	30	15
k_1 = KMIN(LL)	68	135	269	537	1073
f_1 (Hz)	16320	16200	16140	16110	16095
k_2 = KMAX(LL)	83	166	332	664	1328
f_2 (Hz)	19920	19920	19920	19920	19920
k_x = KX(LL)	256	512	1024	2048	4096
f_x (Hz)	61440	61440	61440	61440	61440

of the parameters or variables, which delay and compress or expand the transmitted signal in time, are illustrated in Figure 10 for the l^{th} baud.

Recall $x_l(u)$ is the l^{th} baud of the transmitted signal, which is described by (6). In Figure 10, $x_l(u)$ and $y_l(u)$ are represented with a rectangle for illustration purposes only. Recall $x_l(u)$ is the superposition of $x_{lk}(u)$, for $k_1 \leq k \leq k_2$, over a total of K tones. The frequency of $x_{lk}(u)$ is

$$\omega_k = \omega_x * (k / k_x) \tag{8}$$

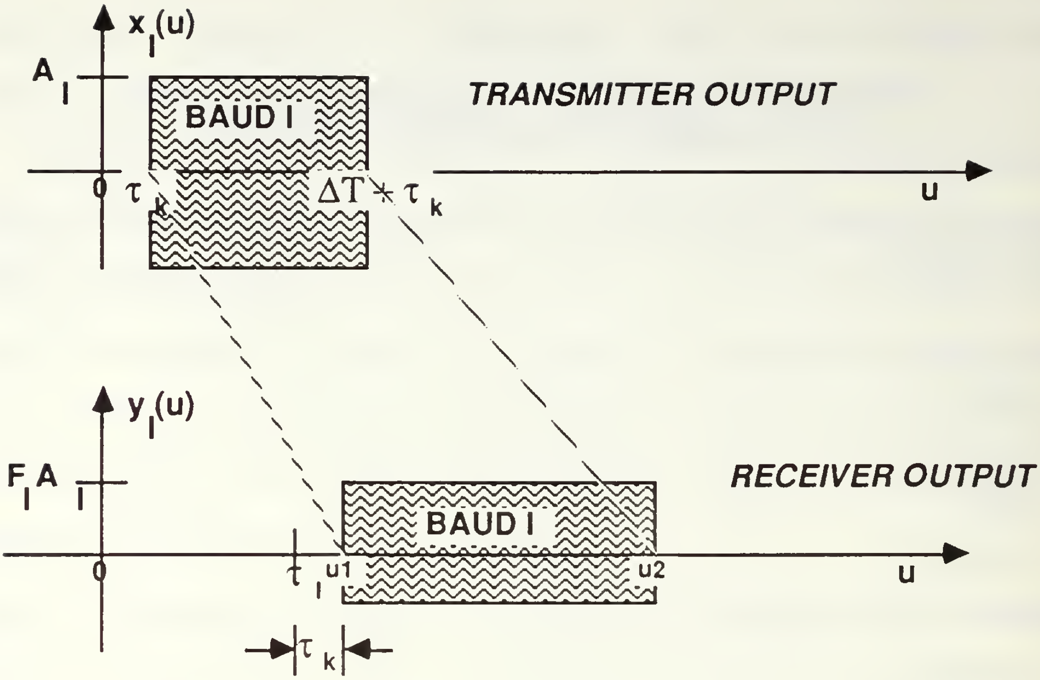


Figure 10. The lth Baud of the Transmitted Signal Delayed and Dilated in Time

where $\omega_x = 2\pi\ f_x$ and f_x is the sampling frequency of the transmitted signal. Table I lists the values of these parameters and the applicable variables which are used in the simulation.

When $x_{lk}(u)$ propagates through the transmitter system, it may be delayed by the transmitter system electronics. In the simulation, this delay is denoted by τ_k = TAUK(K), and is a constant for all k. (In the simulation, TAUK(K) may be set to a constant or to any known function of k.) Acoustic transmission of $x_l(u)$ begins at $u = \tau_k$ and ends at $u = \Delta T + \tau_k$.

When the signal, $x_l(u - \tau_k)$, leaves the moving transmitter, it is delayed and compressed or expanded in time due to the movement of the transmitter and the distance it travels through the channel to the receiver. (The time

delay introduced by the electronics of the receiver has not been included in the simulation.) This time delay and compression/expansion factor will be referred to as £(u). Derivation of £(u) is presented in Appendix A. The time delay and compression/expansion factor due to the medium is described by

$$\pounds(u) = (\tau_l + \alpha_l u) / (1 + \alpha_l) \tag{9}$$

where

τ_l = The time for the l^{th} baud of the transmitted signal to travel through the channel and arrive at the output of the receiver.

α_l = The Doppler compression factor due to the moving transmitter platform.

The parameters, τ_l and α_l, depend on the slant range to the receiver, R(LL), and the speed of sound of the acoustic channel, C(LL), for the l^{th} baud. Recall R(LL) is computed using equation (4). The speed C(LL) is Gaussian distributed with mean = C0 and variance = CVAR. The parameters C0 and CVAR are input by the simulation user. The parameters, τ_l and α_l, are related to R(LL) and C(LL) in the following manner:

$$\tau_l = \mathrm{TAUL(LL)} = \mathrm{R(LL)} / \mathrm{C(LL)} \tag{10}$$

and

$$\alpha_l = \mathrm{ALPHA(LL)} = \dot{\mathrm{R}}\mathrm{(LL)} / \mathrm{C(LL)} \tag{11}$$

where

$$\dot{\mathrm{R}}\mathrm{(LL)} = \frac{[(\mathrm{X(LL)} * \mathrm{VXAVG}) + (\mathrm{Y(LL)} * \mathrm{VYAVG}) + (\mathrm{Z(LL)} * \mathrm{VZAVG})]}{\mathrm{R(LL)}} \tag{12}$$

Recall X(LL), VXAVG, Y(LL), VYAVG, Z(LL), and VZAVG were described in the previous chapter with equations (1) through (3). TAUL(LL) and

ALPHA(LL) are the simulation variables for τ_l and α_l, respectively. When the transmitted signal, $x_l(u - \tau_k)$, arrives at the receiver output, it is compressed/ expanded in time by £ (u).

The received signal is

$$y_l(u) = \sum_{k=k_1}^{k_2} y_{lk}(u) \qquad ; u_1 \leq u \leq u_2 \tag{13}$$

where

$$y_{lk}(u) = F_{lk} A_{lk} \cos(2\pi k \Delta f (u - \tau_k - £(u)) + \Phi_{lk}), \tag{14}$$

and F_{lk} is the attenuation of tone k due to the propagation through the channel. The signal, $y_l(u)$, will begin at time u_1 and end at time u_2. The signal, $x_l(0)$, transmitted at time u = 0 is the same signal, $y_l(u_1)$, that arrives at the receiver at time u_1; and likewise, the signal, $x_l(\Delta T)$, transmitted at time $u = \Delta T$ is the same signal, $y_l(u_2)$, which arrives at the receiver at time u_2 (see Figure 10). Since it is the same signal, the times that this signal arrives at the output of the receiver may be equated to the corresponding times that this signal was sent to yield

$$u_1 = (1 + \alpha_l)\, \tau_k + \tau_l \tag{15}$$

and

$$u_2 = (1 + \alpha_l)\, \Delta T + (1 + \alpha_l)\, \tau_k + \tau_l \ . \tag{16}$$

It is obvious that $y_l(u)$ is also a superposition of signals, $y_{lk}(u)$. However, $y_{lk}(u)$ is at frequency ω_k', where

$$\omega_k' = \omega_k / (1 + \alpha_l) \tag{17}$$

due to the moving transmitter. At the receiver, $y_l(u)$ will be sampled at

$$\omega_y = \omega_x / (1 + \alpha_m) \tag{18}$$

where α_m is the Doppler factor associated with the m^{th} Doppler channel. If $\alpha_l = \alpha_m$, then the frequencies of the received signal are exactly in the center of Doppler channel m. However, in general, α_l will fall between Doppler channels and there will be some residual Doppler mismatch $\alpha_l - \alpha_m$. If the channels are spaced at intervals $\Delta\alpha$, then the maximum mismatch will be $\pm \Delta\alpha/2$. In the following section, a derivation for the spacing of the Doppler channels $\Delta\alpha$ is presented.

C. DOPPLER ESTIMATION AND DOPPLER CHANNELS

Several processing approaches were considered for estimating the channel model parameters. However, the ultimate goal is to send a signal through a bandpass channel using MFQPSK modulation on a succession of bauds which constitute a signal "packet". In the presence of white noise, the optimum receivers for these signals are filters matched to each of the tone/phase combinations. Recall the four phases are $\{\pi/4, 3\pi/4, -3\pi/4, -\pi/4\}$ for a MFQPSK signal. Therefore, a filter matched to the transmitted signal with $\Phi_{lk} = \pi/4$ will have a positive output when $\pi/4$ is sent, a negative output when $-3\pi/4$ is sent, and an output of zero when $3\pi/4$ or $-\pi/4$ is sent, provided that the receiver is synchronized with the signal. Similarly, the output of a filter matched to the transmitted signal with phase equal to $3\pi/4$ is positive when $3\pi/4$ is sent, negative when $-\pi/4$ is sent, and zero otherwise. Also filter pairs matched to the i^{th} frequency of the transmitted signal, $f_i = k_i\Delta f$, produce zero outputs for all phases at the frequency $f_j = k_j\Delta f$ when $k_i \neq k_j$.

To summarize, a matched filter system for MFQPSK signals with K tones and baud length $\Delta T = 1/\Delta f$ consists of K pairs of filters, one filter of each pair matched to phase $\pi/4$ and the other filter of the pair matched to phase $3\pi/4$. Each filter pair output demodulates the phase information encoded on a particular tone.

Since the maximum Doppler shift will be present on the highest frequency or tone in the baud, the response of the filter pair matched to this tone will be analyzed to show how the Doppler channel spacing, $\Delta\alpha$, is derived and how α_m is computed in the simulation.

Let $h_i(u)$ and $h_q(u)$ be the filters matched to the signals:

$$x_{lk_2,i}(u) = A_{lk_2}\cos(2\pi\, k_2\, \Delta f\, u + \pi/4)\ ;\ 0 \le u \le \Delta T \qquad (19a)$$

and

$$x_{lk_2,q}(u) = A_{lk_2}\cos(2\pi\, k_2\, \Delta f\, u + 3\pi/4)\ ;\ 0 \le u \le \Delta T. \qquad (19b)$$

where the indices i and q denote in-phase and quadrature phase, respectively. Thus, $h_i(u)$ and $h_q(u)$ are described as follows:

$$h_i(u) = 2\cos(2\pi\, k_2\, \Delta f\, (\Delta T - u) + \pi/4)\ ;\ 0 \le u \le \Delta T \qquad (20a)$$

and

$$h_q(u) = 2\cos(2\pi\, k_2\, \Delta f\, (\Delta T - u) + 3\pi/4)\ ;\ 0 \le u \le \Delta T. \qquad (20b)$$

Now the received signal from equation (14), given $\pi/4$ is the phase of the tone k_2, is

$$y_{lk_2}(u) = F_{lk_2}A_{lk_2}\cos(2\pi\, k_2\, \Delta f\, (u - \tau_{k_2} - \pounds(u)) + \pi/4)\ ;\ u_1 \le u \le u_2\ . \qquad (21)$$

The received signal, given $3\pi/4$ is the phase of the tone k_2, is similar to (21) with $\Phi_{lk} = 3\pi/4$ instead of $\pi/4$ as above.

As illustrated in Figure 11, the output of the matched filter pair, in general, is the convolution of $h(\tau)$ and $y_{lk}(\tau)$ given by

$$z_{lk,i}(u) = \int_0^{\tau_{max}} h_i(\tau)\, y_{lk}(u - \tau)\, d\tau \tag{22a}$$

and

$$z_{lk,q}(u) = \int_0^{\tau_{max}} h_q(\tau)\, y_{lk}(u - \tau)\, d\tau\ , \tag{22b}$$

where $\tau_{max} = u_2 - u_1$. Evaluating (22a) and (22b), the following expressions are obtained for the output of the matched filter pairs due to tone k_2:

$$z_{lk_2,i}(u) = F_{lk_2} A_{lk_2} \int_0^{\tau_{max}} \cos\left[2\pi k_2 \Delta f(u - £(u - \tau) - \tau_{k_2} - \Delta T)\right] d\tau \tag{23a}$$

and

$$z_{lk_2,q}(u) = F_{lk_2} A_{lk_2} \int_0^{\tau_{max}} \sin\left[2\pi k_2 \Delta f(u - £(u - \tau) - \tau_{k_2} - \Delta T)\right] d\tau \tag{23b}$$

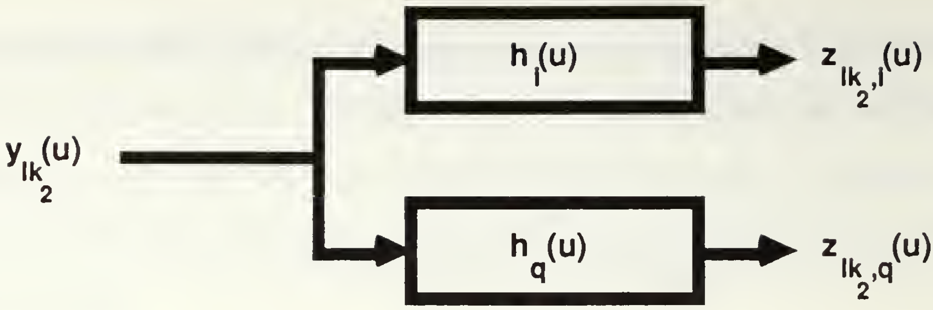


Figure 11. Matched Filter Pair for Tone k_2

Inserting equation (9) for £(u) in the above two equations yields

$$z_{lk_2,i}(u) = F_{lk_2} A_{lk_2} \int_0^{\tau_{max}} \cos\left[(2\pi k_2 \Delta f)\left(u - t_l + \alpha_l \tau - (1+\alpha_l)(\tau_{k_2} + \Delta T)\right)(1+\alpha_l)^{-1}\right] d\tau \tag{24a}$$

and

$$z_{lk_2,q}(u) = F_{lk_2} A_{lk_2} \int_0^{\tau_{max}} \sin\left[(2\pi k_2 \Delta f)\left(u - t_l + \alpha_l \tau - (1+\alpha_l)(\tau_{k_2} + \Delta T)\right)(1+\alpha_l)^{-1}\right] d\tau \tag{24b}$$

Recall that the received signal arrives when $u_1 \le u \le u_2$ with

$$u_1 = [(1 + \alpha_l)\, \tau_k + \tau_l] \text{ and } u_2 = [(1+ \alpha_l)\, \Delta T + (1+ \alpha_l)\, \tau_k + \tau_l] \quad .$$

Also recall from the previous section that α_l is the Doppler compression/ expansion factor due to the moving transmitter. Note that for $\alpha_l \le 0$, $\tau_{max} = u_2 - u_1 \le \Delta T$ and for $\alpha_l > 0$, $\tau_{max} = u_2 - u_1 > \Delta T$. Using $\tau_{max} = \Delta T / (1+\alpha_l)$ for the upper limit in the integration in the convolution integrals (24a) and (24b), will not affect the integrals significantly because α_l is of the order 10^{-3}; therefore, dividing by $(1+ \alpha_l)$ is very close to dividing by 1.

Sampling $z_{lk_2,i}(u)$ and $z_{lk_2,q}(u)$ at $u = u_2$ and evaluating their integrals in (24a) and (24b) from 0 to τ_{max} yields

$$z_{lk_2,i}(u) \Big|_{u=u_2} = F_{lk_2} A_{lk_2} \Delta T\,(1+\alpha_1) \frac{\sin [2\pi k_2 \alpha_l]}{2\pi k_2 \alpha_l} = Z_{lk_2,i}(\alpha_l) \tag{25a}$$

and

$$z_{lk_2,q}(u) \Big|_{u=u_2} = F_{lk_2} A_{lk_2} \Delta T\,(1+\alpha_1) \frac{(1-\cos [2\pi k_2 \alpha_l])}{2\pi k_2 \alpha_l} = Z_{lk_2,q}(\alpha_l)\ . \tag{25b}$$

The total power, P_{lk}, in the k^{th} tone of the l^{th} baud is one-half the amplitude, $F_{lk}A_{lk}$, of the received signal squared. That is

$$F_{lk}A_{lk} = (2\ P_{lk})^{0.5}. \tag{26}$$

Also assume $1+\alpha_l = 1$; therefore, $\Delta T\ (1+\alpha_l)$ is approximately equal to ΔT. With these substitutions, equations (25a) and (25b) become

$$Z_{lk_2,i}(\alpha_l) = (2P_{lk_2})^{0.5} \Delta T \frac{(\sin [2\pi k_2 \alpha_l])}{2\pi k_2 \alpha_l} \tag{27a}$$

and

$$Z_{lk_2,q}(\alpha_l) = (2P_{lk_2})^{0.5} \Delta T \frac{(1-\cos [2\pi k_2 \alpha_l])}{2\pi k_2 \alpha_l}\ . \tag{27b}$$

A graph of $Z_{lk_2,i}(\alpha_l)$ and $Z_{lk_2,q}(\alpha_l)$ from (27a) and (27b), respectively, is shown in Figure 12.

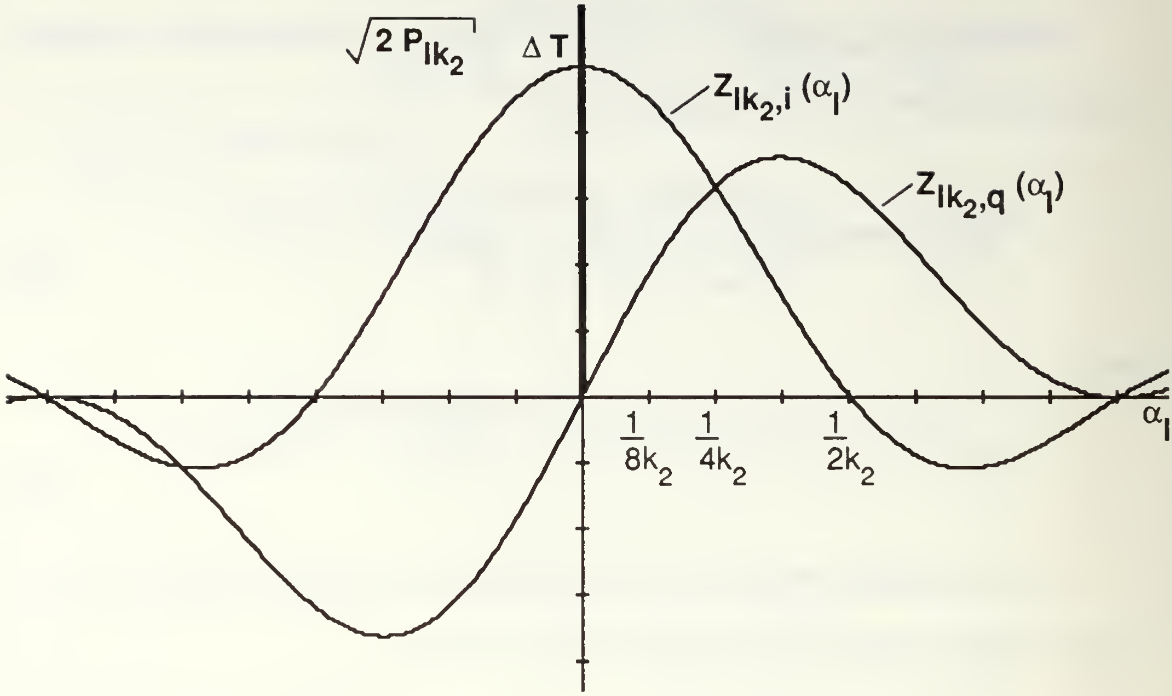


Figure 12. Matched Filter Outputs Versus Doppler Shift

Note that at $\alpha_l = 1/(4\ k_2)$, $|\ Z_{lk_2,i}\ | = |\ Z_{lk_2,q}\ |$; this is illustrated in Figure 12. This means that the response of the in-phase and quadrature channels are equal even though an in-phase $\pi/4$ symbol was sent; therefore, a significant decoding error would be made if $\alpha_l = 1/(4\ k_2)$. It is obvious that, at $\alpha_l = 0$, $Z_{lk_2,i}(0)$ is maximum and $Z_{lk_2,q}(0)$ is zero; in which case, no decoding errors would be made. The ratio of $Z_{lk_2,i}$ to $Z_{lk_2,q}$ below, evaluated for various α_l's less than $1/(4\ k_2)$, produces the maximum width of the Doppler channels, $\Delta\alpha$.

The ratio is described by:

$$\frac{Z_{lk_2,i}}{Z_{lk_2,q}} = \frac{\sin(2\pi k_2\alpha_l)}{1 - \cos(2\pi k_2\alpha_l)} \ . \tag{28}$$

For $\alpha_l = 1/(16\ k_2)$, the ratio above is ≥ 5.03 which is 14 dB. This is called inter-symbol separation.

The value of 14 dB was considered the minimum amount of inter-symbol separation to be tolerated. Recall that the maximum amount of Doppler mismatch is $\alpha_l\text{-}\alpha_m=\pm\Delta\alpha/2$. Therefore, $\Delta\alpha$, the Doppler channel spacing, is equal to $1/(8\ k_2)$ and the magnitude of the maximum amount of residual Doppler mismatch is $\Delta\alpha/2 = 1/\ (16\ k_2)$, where α_m is the Doppler factor associated with the m^{th} Doppler channel. In the simulation, $\Delta\alpha$ = DELALF(LL) = 1/(8*KMAX(LL)).

Solving $\alpha_l - \alpha_m = \pm\ \Delta\alpha/2$ for α_m, yields

$$\alpha_m = \alpha_l \pm \Delta\alpha/2 \ , \tag{29}$$

where α_m, the Doppler factor due to the m^{th} Doppler channel, is equal to $m\ \Delta\alpha$. Substituting α_m=$m\ \Delta\alpha$ into (29) yields the following expressions for the lower bound, m_1, and upper bound, m_2, of m, the Doppler channel number as

$$m_1 = (\alpha_l\ /\ \Delta\alpha) - 0.5 \tag{30a}$$

and

$$m_2 = (\alpha_l\ /\ \Delta\alpha) + 0.5 \ . \tag{30b}$$

Since m is an integer between m_1 and m_2, it is computed as

$$m = \text{int}[(m_1 + m_2)/2]. \tag{31}$$

In the simulation, m = M(LL) and is computed using (31); and

$$\alpha_m = \text{ALPHAM(LL)} = \text{M(LL)} * \text{DELALF(LL)}.$$

D. THE ATTENUATION FACTOR DUE TO AN ACOUSTIC CHANNEL

When the transmitted signal, $x_{lk}(u - \tau_k)$, travels through the medium or channel, its amplitude will be attenuated by a factor F_{lk} due to the channel. In the simulation, the user has the input option to have this attenuation applied to the received signal or to let all the received signal tones have equal amplitudes. The quantity AA(LL,K) is the amplitude of the l^{th} baud and k^{th} tone of the simulation's received signal. If the user chooses to have equal amplitudes, then AA(LL,K) is set equal to 1 for all LL and all K. If the user desires the attenuation to be put on the received signal, then AA(LL,K) = F_{lk}, which is computed below.

In general, the transmission loss depends on frequency, depth, pressure, and temperature. However, when specific propagation conditions are of no interest and only a rough approximation of the transmission loss is adequate; the spherical-spreading law plus an added loss due to absorption is equal to the transmission loss [Ref. 4]. Therefore, the transmission loss in dB is

$$TL = (20 \log_{10} R) + \beta R \tag{32}$$

where

R is the depth of the receiver from the surface in feet and

β is the attenuation coefficient due to absorption in dB per foot.

Thus, the following expression for F_{lk} is used in the simulation:

$$F_{lk} = 10^{-(TL/20)}. \tag{33}$$

The attenuation coefficient, β, is described by [Ref. 4]

$$\beta = \left(\frac{0.1\, f^2}{1 + f^2} + \frac{40\, f^2}{4.100 + f^2} + (0.000275)\, f^2 + 0.003 \right) (3000)^{-1} \tag{34}$$

where

$$f = (k\ \Delta f) / 1000 \text{ in kilohertz.}$$

This expression applies for a temperature of 39°F (4°C), which is an average seawater temperature, and a depth of about 3000 feet. The constant 0.003 is added to take care of the attenuation at very low frequencies [Ref. 4]. In the simulation, ABSORP = β.

The absorption of seawater decreases by about 2 percent for every increase of 1000 feet in depth [Ref. 4]. Note in the simulation, the transmitter is at a depth of 1000 feet below the ocean's surface. This depth is set with the simulation variable TXDEP. Thus, the receiver is R = TXDEP + Z(LL) below the ocean's surface. TXDEP is not an input of the simulation; therefore, to change TXDEP from 1000, one must change TXDEP in the simulation code. The simulation computes β using equation (34), then increases β by 2 percent for every 1000 feet that the receiver's depth exceeds 3000 feet from the

ocean's surface or decreases β by 2 percent for every 1000 feet that the receiver's depth is less than 3000 feet from the ocean's surface.

E. THE SAMPLED RECEIVED SIGNAL WITHOUT NOISE

The received signal, $y_l(u)$, is sampled at an interval

$$\Delta u = [\Delta T\,(1 + \alpha_m)] \,/\, k_x \;. \tag{35}$$

(Recall $\omega_y = 2\pi\, k_x \,/\, [(1 + \alpha_m)\,\Delta T]$, (18), is the sampling frequency.) The parameters ΔT and k_x are defined in section A. The Doppler factor, α_m=m $\Delta\alpha$, associated with the m^{th} Doppler channel was derived in the previous section. The first sample will be taken at $\hat{u}_l$, which is the best estimate of u_l, the beginning or synchronization point of the l^{th} baud at the receiver. This is illustrated in Figure 13. The synchronization error of the l^{th} baud is $\Delta u_l = u_l - \hat{u}_l$. The simulation variable names for the above parameters are u_l=U1, $\hat{u}_l$=UHAT1, and Δu_l=DELU1.

The sampled received signal for the l^{th} baud is (13) with u = $n\Delta u + \hat{u}_l$. When $\hat{u}_l = u_l$, the sampled received signal for the l^{th} baud is (13),

$$y_l(n) = y_l\,(n\Delta u + u_l) = \sum_{k=k_1}^{k_2} y_{lk}(n\Delta u + u_l) \qquad ; \quad 0 \le n \le (k_x - 1) \tag{36}$$

where

$$y_{lk}(n\Delta u + u_l) = F_{lk}A_{lk}\cos[2\pi k\,\Delta f\,(n\,\Delta u - (\pounds(n\,\Delta u + u_l) - \pounds(u_l))) + \Phi_{lk}]. \tag{37}$$

Substituting (9) for $\pounds(u)$ and computing $\pounds(n\,\Delta u + u_l) - \pounds(u_l)$ yields

$$\pounds(n\,\Delta u + u_l) - \pounds(u_l) = (\alpha_l\, n\,\Delta u) \,/\, (1 + \alpha_l). \tag{38}$$

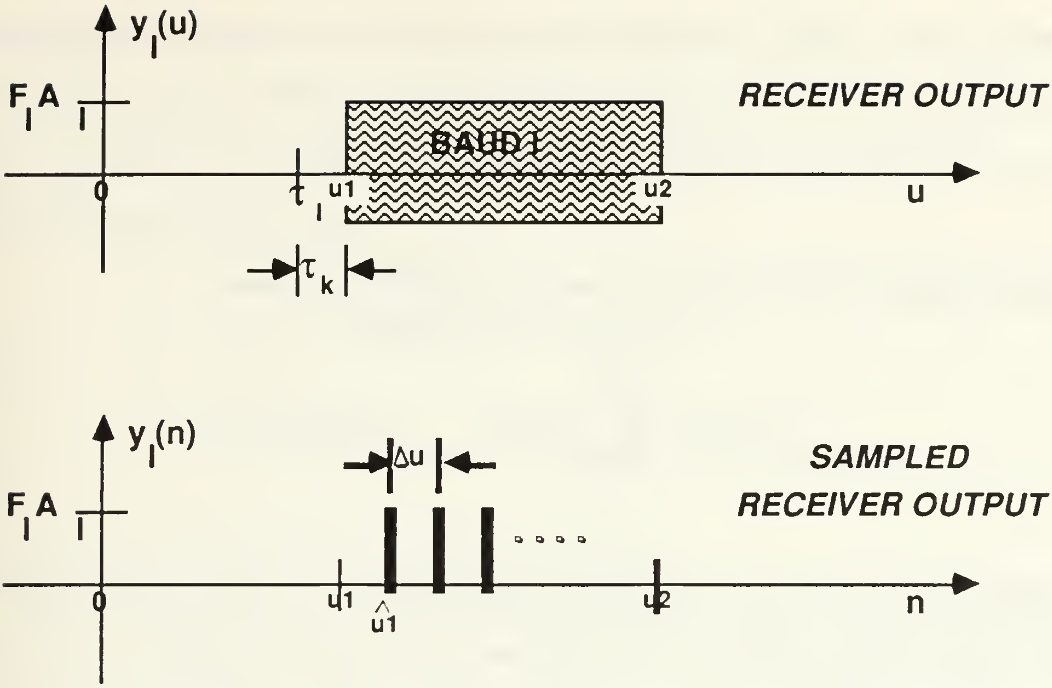


Figure 13. The Sampled Receiver Output

Now substituting $\Delta u = [\Delta T\,(1 + \alpha_m)] / k_x$ into (38) produces

$$\pounds(n\,\Delta u + u_1) - \pounds(u_1) = [\alpha_l\, n\, \Delta T\,(1 + \alpha_m)] / k_x\,(1 + \alpha_l). \tag{39}$$

Collecting the results from (39) and $n\Delta u = [n\,\Delta T\,(1 + \alpha_m)] / k_x$ together and substituting them into (37) yields the following sampled received signal for the l^{th} baud and k^{th} tone:

$$y_{lk}(n) = F_{lk}A_{lk}\cos[(2\pi k/k_x)\,((1{+}\alpha_m) / (1{+}\alpha_l))\,n + \Phi_{lk}]. \tag{40}$$

If a factor ν_{lk} is added to n to account for random timing jitters of the l^{th} baud and k^{th} tone due to synchronization error, then (40) becomes

$$y_{lk}(n) = F_{lk}A_{lk}\cos[(2\pi k/k_x)\,((1{+}\alpha_m) / (1{+}\alpha_l))\,(n - \nu_{lk}) + \Phi_{lk}] \tag{41}$$

$$\text{for } 0 \le n \le (k_x - 1)\,,$$

where

$$\nu_{lk} = \frac{\Delta u_1 \, k_x}{\Delta T \, (1+\alpha_m)} \,. \tag{42}$$

Finally summing (41) over all the tones in the l^{th} baud gives

$$y_l(n) = \sum_{k=k_1}^{k_2} y_{lk}(n) \qquad ; \quad 0 \le n \le (k_x - 1) \,. \tag{43}$$

Summarizing, (41) is the final computational form of the received signal which is denoted by YY in the simulation. The received signal, YY, is then summed over all the k's for each baud from KMIN(LL) to KMAX(LL) to yield YRX in the simulation, which is $y_l(n)$ above. In the simulation, all the packets are contiguous. The continuous sampled received signal is YYRX(II) where II ranges from 0, which is the first sample of the first baud (LL=1) in the first packet, to NPTS, which is the last sample of the last baud (LL = BDTOTL = the total number of bauds) in the last packet. YYRX(II) is equal to YRX plus NOISE with all the packets contiguous and the bauds within each packet contiguous, where NOISE is white Gaussian noise added to the received signal. NOISE, which depends on the input signal-to-noise ratio (SNR), is described in the next section.

F. SIGNAL PLUS ADDITIVE NOISE

Inevitably noise will be added to the signal, either from the environment, the electronics, or both. This noise is assumed to be additive white Gaussian noise. Since it is assumed that the received signal, $y_l(u)$, has been ideally

bandlimited to one-half the sampling frequency, there is no power in frequencies greater than or equal to $f_x/2$. Recall that the signal is sampled at the transmitter at f_x. If w(u) is white noise and has the white power spectral density equal to $N_o/2$, then

$$E[\, w(u) \,] = E[\, w(n) \,] = 0 \tag{44}$$

and

$$\sigma^2 = VAR[\, w(u) \,] = VAR[\, w(n) \,] = N_o\, f_x/2, \tag{45}$$

where w(n) is the white noise sequence [Ref. 1].

Let the receiver input SNR be defined as the signal power in bandwidth W divided by the noise power in bandwidth W. The average tone signal power in the l^{th} baud is defined as

$$PAVG_l = (1/K) \sum_{k=k_1}^{k_2} P_{lk} \tag{46}$$

where P_{lk} is the total power in the k^{th} tone of the l^{th} baud. (Recall that K is the total number of MFM tones in the l^{th} baud.) Therefore, the wideband input SNR for the l^{th} baud [Ref. 1] is

$$SNRWB_l = (K\, PAVG_l) / (W\, N_o) = PAVG_l / (\Delta f\, N_o) = PAVG_l\, k_x / (2\, \sigma_l^2), \tag{47}$$

because $\Delta f = f_x / k_x$ and $N_o = (2\, \sigma_l^2) / f_x$. The narrowband input SNR for the l^{th} baud is

$$SNRNB_l = P_{lk} / (\Delta f\, N_o) = P_{lk}\, k_x / (2\, \sigma_l^2). \tag{48}$$

Note that if all the tones have equal amplitudes (i.e., AA(LL,K) = 1), then $PAVG_l$ is equal to P_{lk}; in which case, $SNRWB_l = SNRNB_l$.

Solving (47) for σ_l^2 yields

$$\sigma_l^2 = [(1/K) \sum_{k=k_1}^{k_2} P_{lk}]\, k_x / (2\ \mathrm{SNRWB}_l) \quad . \tag{49}$$

Recall $P_{lk} = (AA_{lk}^2) / 2$, where AA_{lk} is the amplitude of the k^{th} tone and l^{th} baud of the received signal. In the simulation, NOISE is added to the received signal, $y_l(n)$ = YRX, which is white Gaussian noise with zero mean and variance = σ_l^2 computed in (49). A single input wideband SNR is input by the simulation user for all bauds, l. The following simulation variables are used for the above parameters:

σ_l^2 = NOSVAR(LL),

K = KPTS(LL),

AA_{lk} = AA(LL,K),

k_x = KX(LL), and

SNRWB_l = SNRIN.

IV. TESTING THE SIMULATION AGAINST MFQPSK THEORY

A. BACKGROUND

The purpose of developing this simulation was to create an experimental tool to test and analyze various Doppler, synchronization, and coding techniques and/or algorithms to support the implementation and testing of an MFQPSK acoustic link. Before the simulation could be used in this capacity, it had to be tested against MFQPSK signal theory. There was no actual test data to use for comparison; therefore, tests were performed to verify that the simulation output, the received signal, agrees with the theory of MFQPSK signals. It is anticipated that the simulation will be tested further when actual test data is available.

It has been shown that, in theory, the output SNR (SNR_{OUT}) equals the input narrowband SNR ($SNRNB_{IN}$) for MFQPSK signals in additive white Gaussian noise memoryless channels that are demodulated coherently with a Discrete Fourier Transform (DFT) [Ref. 1]. The results of testing the simulation's ability to reproduce this result are described and presented below.

B. THE TESTING METHODOLOGY

The following approach was taken to verify that the simulation performs at an acceptable level (i.e., $SNR_{OUT} = SNRNB_{IN}$). A set of 5 signal packets were generated with the simulation with a given input wideband SNR ($SNRWB_{IN}$). Each packet contained a single unique baud type; therefore, each simulation run consisted of the 5 different baud types. Referring to Table I, the 5 different baud types are

Baud Type 1: 256 sample points,

Baud Type 2: 512 sample points,

Baud Type 3: 1024 sample points,

Baud Type 4: 2048 sample points, and

Baud Type 5: 4096 sample points.

Recall from Chapter III that if all the tones have the same power within a baud (i.e., the amplitudes of tones within a baud are all equal), then the input wideband SNR is equal to the input narrowband SNR for that baud. All the runs used for this analysis were produced with normalized amplitudes within each baud. The phases that were transmitted were generated randomly by the computer code.

It is known that the minimum input SNR required to accurately decode MFQPSK is approximately 15 dB. This analysis considered input narrowband SNRs from 0 to 20 dB. The initial conditions for the transmitter's position and velocity were chosen from the NOSC track data. These initial conditions are

X0 = -5.0 feet, VXAVG = 1.0 ft/sec, VXVAR = 0.0025 $(\text{ft/sec})^2$,

Y0 = 5.0 feet, VYAVG = 5.4 ft/sec, VYVAR = 0.0025 $(\text{ft/sec})^2$,

Z0 = -5400.0 feet, VZAVG = 0.0 ft/sec, and VZVAR = 0.0025 $(\text{ft/sec})^2$.

The initial conditions for the speed of sound was C0=4900 ft/sec and CVAR=0. Note the transmitter was placed almost directly above the receiver to reduce the amount of Doppler shift in the received signal. A description and examples of the simulation inputs and outputs are presented in Appendix B.

An average output SNR was estimated for each baud using the real and imaginary parts of the received signal's DFT. A k_x-point DFT was performed on each baud of the received signal to decode the phase of the received signal. (The real and imaginary parts of the received signal's DFT contain the phase information sent on each of the tones between harmonic numbers k_1 and k_2 in each baud.) If $\Phi_{lk} = \pi/4$ was transmitted (which is in the first quadrant), then the received signal DFT's real and imaginary parts should be located in the first quadrant (i.e., the real and imaginary parts should be positive). Likewise, for a transmitted phase angle of $3\pi/4$, $-3\pi/4$, or $-\pi/4$ the received signal's DFT phase angle (i.e., real and imaginary parts) should lie in the second, third, or fourth quadrant, respectively. The conditional distributions within each baud were produced by categorizing the DFT's real and imaginary parts on a tone-by-tone basis given the phase that was transmitted on each tone between harmonic numbers k_1 and k_2. There are two distributions of the received signal DFT in each of the four quadrants, a distribution of the real part and one of the imaginary part. The real and imaginary parts are statistically independent [Ref. 1].

For example, in baud type 5 there are 4096 samples of the 256 tones encoded with phase information between harmonic numbers k_1=1073 and k_2=1328. There should be approximately 64 (i.e., one fourth of 256) tones transmitted and received in each quadrant because the four transmitted phases were generated randomly from a uniform distribution. The distribution of each DFT component should be close to a Gaussian distribution.

Once the DFT of K tones in each baud were conditionally partitioned by knowing the transmitted phase (i.e., quadrant) into the four quadrants, then

the sample mean and variance were computed on each of 4 real part distributions and each of the 4 imaginary part distributions. The sample means are, $\overline{R}_i$ and $\overline{I}_i$, where the subscript i denotes the quadrant number. The sample means for each quadrant in a baud are

$$\overline{R}_i = (1/N_i) \sum_{j=1}^{N_i} R_{ij} \quad \text{for } i = 1, 2, 3, \text{ or } 4 \tag{50}$$

and

$$\overline{I}_i = (1/N_i) \sum_{j=1}^{N_i} I_{ij} \quad \text{for } i = 1, 2, 3, \text{ or } 4 \tag{51}$$

where

N_i = the number of times the phase corresponding to quadrant i was sent in that baud

R_{ij} = the j^{th} real part of the received signal's DFT corresponding to a harmonic number that was transmitted with phase in quadrant i

I_{ij} = the j^{th} imaginary part of the received signal's DFT corresponding to a harmonic number that was transmitted with phase in quadrant i.

The sample variances of a given quadrant in a baud are

$$S^2_{R,i} = [1/(N_i-1)] \sum_{j=1}^{N_i} (R_{ij} - \overline{R}_i)^2 \tag{52}$$

and

$$S^2_{I,i} = [1/(N_i-1)] \sum_{j=1}^{N_i} (I_{ij} - \overline{I}_i)^2 . \tag{53}$$

The output SNRs for the i^{th} quadrant within a baud were estimated by the sample mean squared divided by the sample variance as follows [Ref.1]

$$\widehat{SNROUT}_{R,i} = (\overline{R}_i)^2 / S^2_{R,i} \tag{54}$$

and

$$\widehat{SNROUT}_{I,i} = (\overline{I}_i)^2 / S^2_{I,i} \ . \tag{55}$$

The mean squared value of the real and imaginary parts of the DFT is a measure of the signal power received in that quadrant. The variance of the real and imaginary parts is a measure of the noise received in that quadrant. These values form an estimate of the output SNR. Appendix C contains the statistics for the real and imaginary distributions of each of the four quadrants and the overall statistics for each baud.

To derive an estimate of the output SNR for each baud, the real and imaginary distributions of each quadrant were averaged over all four quadrants. There were 2K points in the overall mean and in the overall variance due to the K real parts and K imaginary parts. $\widehat{SNROUT}$ is the overall mean squared divided by the overall variance. Figure 14 is a plot of $\widehat{SNROUT}$ versus the input narrowband SNR, where $\widehat{SNROUT}$ is described by

$$\widehat{SNROUT} = \frac{\left(\sum_{i=1}^{4}\left[N_i\left|\overline{R}_i\right| + N_i\left|\overline{I}_i\right|\right]\right) \Big/ \left(2\sum_{i-1}^{4} N_i\right)}{\left(\sum_{i=1}^{4}\left[\left(N_i-1\right) S^2_{R,i} + \left(N_i-1\right) S^2_{I,i}\right]\right) \Big/ \left(\left(2\sum_{i=1}^{4} N_i\right) - 1\right)} \tag{56}$$

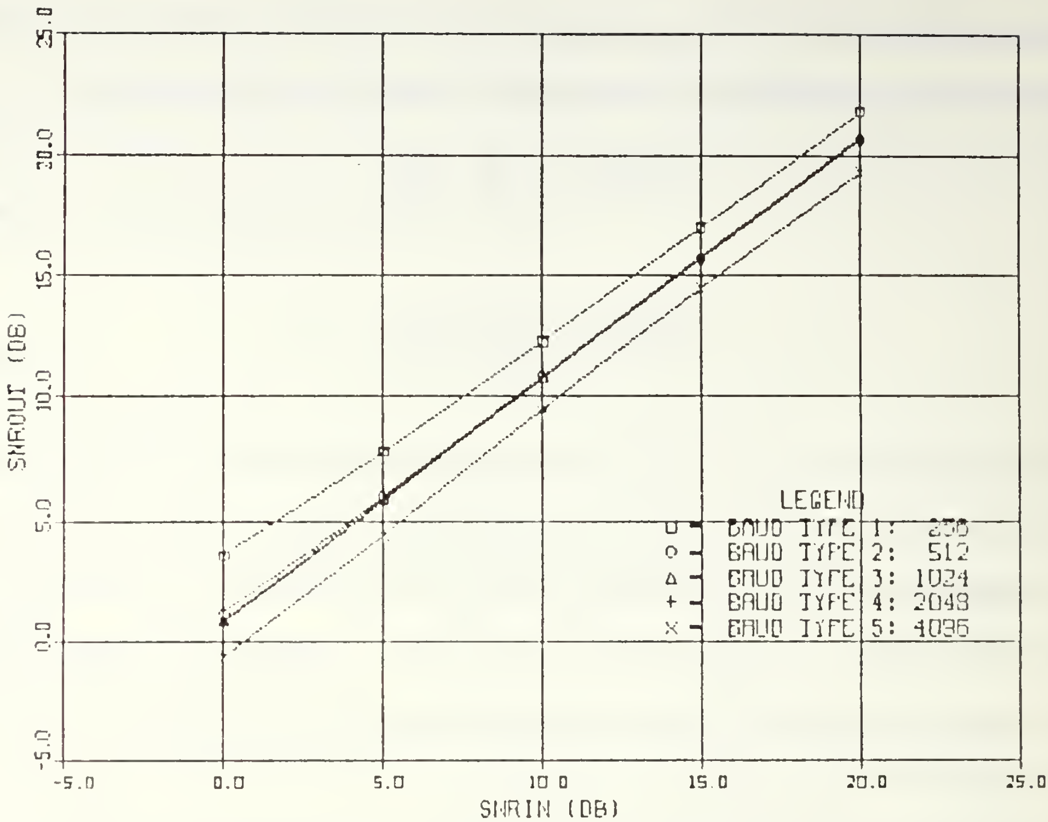


Figure 14. SNR_{OUT} vs. SNR_{IN} for Five Different Bauds

where

$$\sum_{i=1}^{4} N_i = K$$

is the total number of MFM tones in each baud (see Chapter III, Section A).

Note that the absolute value of the sample means must be used in the estimate (56), because, if they are not used, the overall mean will always be close to zero. This is due to the fact that the eight sample means are approximately equal in magnitude, but four have opposite signs due to their quadrant location.

C. RESULTS

If the simulation results agree with the MFQPSK theory, then the input narrowband SNR should equal the output SNR. As can be seen in Figure 14, baud types 2, 3, and 4 agree within one dB with the MFQPSK theory. The longest baud, baud type 5, and the shortest baud, baud type 1, produce estimated output SNRs that are within two dB of the input SNR. As the input SNR increases, it can be observed from Figure 14 that the output SNRs for baud types 1 and 5 converge towards the value of the input SNR.

In conclusion, the output SNR is approximately equal to the input narrowband SNR; therefore, the simulation reproduces what the MFQPSK theory predicts.

V. OUTPUT SNR DEGRADATION DUE TO DOPPLER

A. BACKGROUND

When the MFQPSK signal is transmitted from a moving platform, Doppler will shift the received signal's frequencies. The received signal (at frequency ω_k', (17),) is sampled at ω_y, (18), baud by baud. In general, α_l, the time Doppler compression/expansion factor, does not equal α_m, the Doppler factor set for the m^{th} Doppler channel; hence, there will be some Doppler mismatch. This mismatch will cause degradation in the output SNR.

The output SNR degradation versus the Doppler mismatch was simulated and compared to theory. If inter-symbol interference (ISI), which is energy leaking from one tone to the next tone, is negligible, then the output SNR should degrade due to the Doppler mismatch as $\text{sinc}(\pi\varepsilon/4)$ from (27a) where $\varepsilon = \alpha_l/\Delta\alpha$. Derivation of the theoretical degradation and the comparison to the simulation results follows.

B. ANALYSIS APPROACH

The simulation was run several times. Each run generated one signal packet with an input narrowband SNR = 15 dB. (The values of 15 dB is considered to be the minimum input SNR required to decode the MFQPSK signal.) A packet consisted of five bauds of baud type 3 (i.e., k_x = 1024 points and K = 64 tones). Baud type 3 was chosen based on the results of the simulation versus MFQPSK theory in the previous chapter. Recall that baud type 3 was in close agreement with the theory of MFQPSK signals (i.e., $SNR_{OUT} = SNRNB_{IN}$). The Doppler channel, m, was set to zero for all the

packets. If m = 0, then $\alpha_l - \alpha_m = \alpha_l - m\,\Delta\alpha = \alpha_l$. Thus, by increasing α_l, the amount of Doppler mismatch increases.

Each packet was generated with a different fixed value of $\alpha_l = \varepsilon\,\Delta\alpha$, where ε was fixed at 0, 0.25, 0.5, 0.75, 1.0, ..., 2.5, 2.75 and $\Delta\alpha = 1/(8k_2)$. There were 12 packets generated, one for each value of ε. The phases in the passband of each baud were selected randomly in the simulation. The initial conditions on the transmitter position and velocity and the speed of sound were the same as used in the earlier simulation analysis of the previous chapter.

For each baud, the conditional statistics based on knowing the transmitted phase (i.e., quadrant) and an estimate of the output SNR (56) were computed with the method described in the previous chapter. A packet's estimated output SNR, $\overline{\widehat{\mathrm{SNROUT}}(\varepsilon)}$, is simply the average of the estimated output SNR's from each of the five bauds within that packet. $\overline{\widehat{\mathrm{SNROUT}}(\varepsilon)}$ is

$$\overline{\widehat{\mathrm{SNROUT}}(\varepsilon)} = (1/5) \sum_{i=1}^{5} \widehat{\mathrm{SNROUT}}(\varepsilon)_i \quad . \tag{57}$$

Theoretically, if ISI is neglected, the output SNR, $\mathrm{SNR_{OUT}}$ should degrade due to Doppler, α_l, from (26a) as $(\mathrm{SNR_{IN}}\ \mathrm{sinc}^2(2\pi\, k_2\, \alpha_l))$. Substituting $\alpha = \varepsilon\,\Delta\alpha = \varepsilon / (8\, k_2)$ yields

$$\mathrm{SNR_{OUT}} = \mathrm{SNR_{IN}} + 20 \log_{10} [\sin(\pi\varepsilon/4)/(\pi\varepsilon/4)] \tag{58}$$

where $\mathrm{SNR_{OUT}}$ is in dB. For this analysis, the input SNR, $\mathrm{SNR_{IN}}$, was equal to 15 dB. $\overline{\widehat{\mathrm{SNROUT}}(\varepsilon)}$ and $\mathrm{SNR_{OUT}}$ were plotted versus ε to compare the simulation results with the theoretical degradation for an input SNR of 15 dB (see Figure 15).

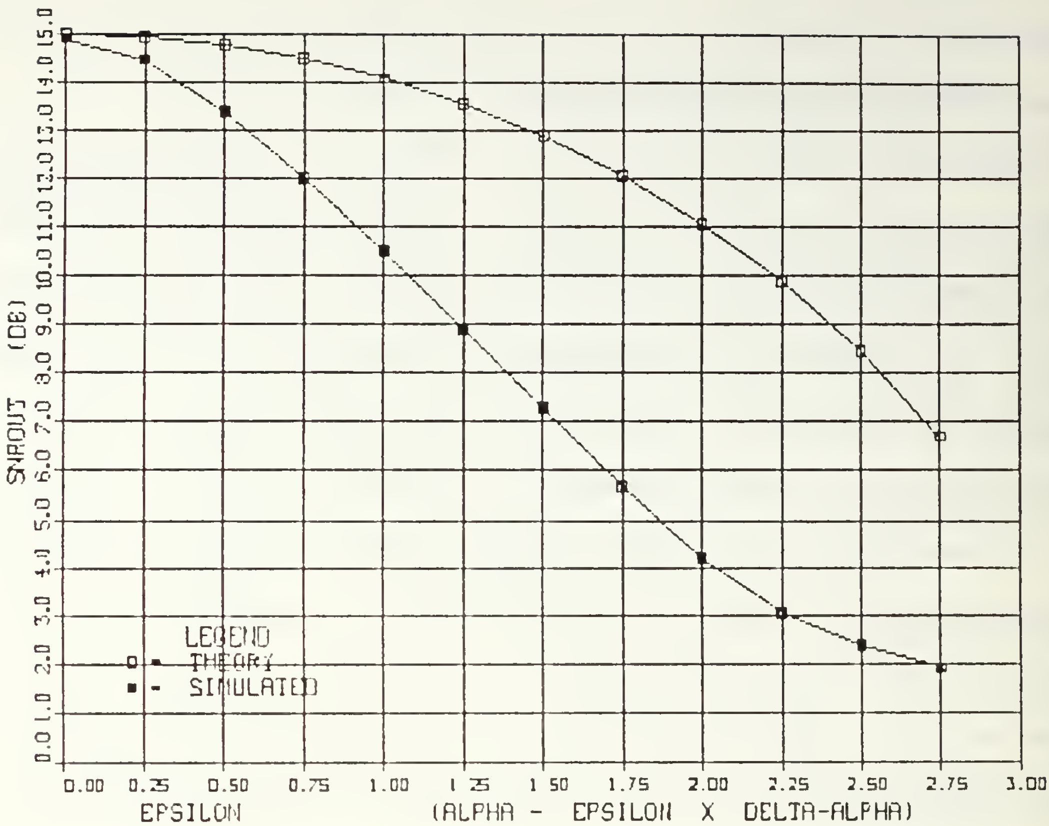


Figure 15. SNR_{OUT} vs. ALPHA for SNR_{IN} = 15 dB

C. RESULTS AND CONCLUSIONS

There is a significant difference between the simulation results and theory as shown in Figure 15. It was speculated that this difference is due to ISI. As α_l increases, the tones "smear" into adjacent tones (i.e., ISI). To prove whether or not the difference was due to ISI, the analysis was repeated with an input SNR of 5 db. By lowering the input SNR to 5 dB, the signal level is not much higher than the noise level within the band; therefore, symbol interference from adjacent tones is at about the same level as the noise level of

that tone. The noise level of each tone, at SNR_{IN} = 5 dB, did not increase as much relative to increases in α_l as when SNR_{IN} = 15 dB; thus, the output SNR at a given tone should not degrade as rapidly as α_l increases. Figure 16 is a plot of the theoretical degradation and the simulation results for both input SNR's (5 and 15 dB). By examining Figure 16 one can see that, indeed, the output SNR at 5 dB degrades at a much slower rate than the output SNR at 15 dB. The statistics of each packet for both 5 and 15 dB input SNR on a baud by baud basis are presented in Appendix D.

The analysis of the simulation results for 15 and 5 dB seemed to substantiate that ISI can not be neglected. An estimate and correction of Doppler shift may be used to reduce the ISI and lessen the output SNR degradation at higher SNR_{IN}'s. An estimate of the Doppler shift can be fed back into the receiver sampling system to compensate for the Doppler shift.

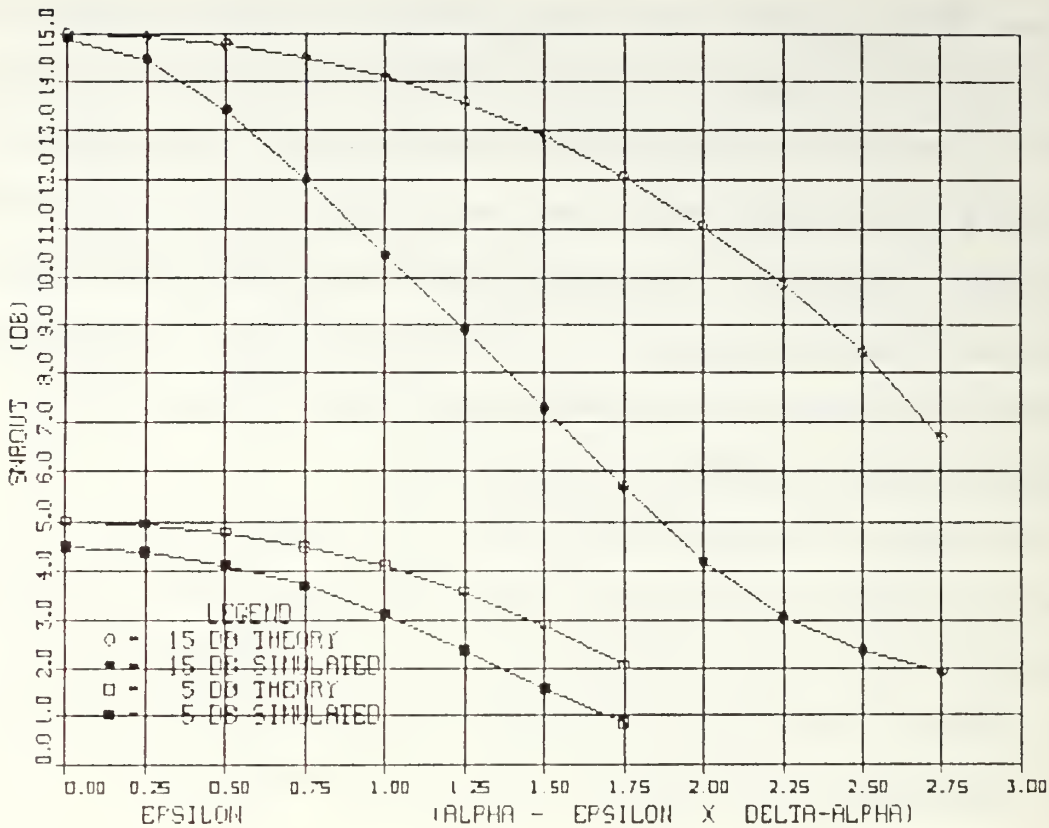


Figure 16. SNR_{OUT} vs. ALPHA for SNR_{IN} = 15 dB and 5 dB

VI. A DOPPLER ESTIMATE FOR FINE CORRECTIONS

A. BACKGROUND

The Doppler shifts due to the moving transmitter should be estimated so that they can be removed from the received signal in the receiver system to reduce the errors in decoding the MFQPSK signal. One technique for estimating the Doppler compression/expansion factor was examined. An adaptation of a Doppler estimation method recently proposed for ordinary QPSK [Ref. 5] was developed for use with MFQPSK and is the subject of this chapter.

B. IMPLEMENTATION OF THE DOPPLER ESTIMATION

This Doppler estimation method approximates the Doppler time compression/expansion factor within a single baud. To implement this estimator, several simulation runs were produced. A simulation run consisted of a single packet. In each packet, five bauds of baud type 3 (i.e., $k_x = 1024$ points and $K = 64$ tones between harmonics 269 and 332) were generated with randomly selected phases. The initial conditions of the transmitter's position and velocity are the same as used in the simulation versus MFQPSK theory in Chapter IV. Each packet was generated with m, the Doppler channel number, equal to zero (i.e., $\alpha_m = 0$, which means the residual Doppler mismatch, $\alpha_l - \alpha_m$, is equal to α_l) and a fixed $\alpha = \alpha_l = \varepsilon\, \Delta\alpha$ where ε is between 0 and 1.5 and $\Delta\alpha = 1/(8k_2)$. For this analysis (using baud type 3), k_2 is 332; therefore, $\Delta\alpha = 1/2656$. Recall $\alpha = \alpha_l$ is the Doppler compression/expansion factor. A set of runs or packets were produced for four different input

narrowband SNR's (10, 15, 20, and 40 dB). The amplitudes for all the packets were normalized (i.e., AA(LL,K) = 1 for all LL and K).

Comparison of the phase for a given tone in the first half of a baud to the phase of the same tone in the second half of the baud yields an estimate of the Doppler compression/expansion factor within that baud. If there is no Doppler shift and no noise on the signal, the corresponding phases from the first and last half of the baud should be equal. The following method was used to compute $\hat{\alpha}_l$ which is an estimate of the Doppler compression/expansion factor within the l^{th} baud. To obtain the phases of the first and second half of the received signal's baud, a 512 (i.e., $k_x/2$) point DFT was taken on the first 512 points of the baud and another 512 point DFT was taken on the last 512 points of the baud. Note that, when the bauds were generated with the simulation, the odd tones within the passband (harmonics between 269 and 332) were zeroed out by setting their amplitudes to zero (all the harmonics outside the passband are always zero). If the odd harmonics in the passband are not zero, then the output of the DFT's of the first and last halves of the baud will have interference between harmonic numbers because 1/2 of an odd harmonic does not produce an integer harmonic, causing an extra half cycle of signal between the harmonics, k', of the 512 point DFT's. With an ideal received signal (i.e., no noise and no Doppler), if the odd harmonics in the passband are nonzero, the corresponding phases of the harmonics of the first and last half of the baud will not be equal due to the interference of the signals between each harmonic in the 512 point DFT's.

A Doppler estimate, $\hat{\alpha}_l$, was then computed for each baud by averaging the differences between the received signal's phases from the first half and

the received signal's phases from the second half of the baud. Thus, the Doppler compression/expansion factor estimate for a baud is

$$\hat{\alpha}_l = [1/(K/2)] \sum_{k'} [\text{PHASE of } (S2^*(k')\, S1(k'))] / (2\pi k') \tag{59}$$

where,

$S2^*(k')$ = Conjugate of the DFT of the second half of the baud
$S1(k')$ = The DFT of the first half of the baud
k' = A harmonic number of the first and second half DFT's (Note $k' = k/2$, where k are the harmonics of the original k_x point DFT of the baud.)
K = The number of MFM tones in the original baud.

An average Doppler estimate, $\hat{\alpha}$, was calculated for each packet by averaging the five Doppler estimates, $\hat{\alpha}_l$, within each packet and was plotted versus α for each of the four input SNRs (see Figure 17). Appendix E contains the estimates and statistics for each packet at each input SNR.

C. RESULTS AND CONCLUSIONS

From the analysis for $\alpha = \alpha_l$ between 0 and 1.5 $\Delta\alpha$, $\hat{\alpha}$ does not estimate α accurately for input SNRs less than 15 dB. Recall that an input SNR = 15 db is the minimum for successfully decoding this MFQPSK signal. At an input SNR of 15 dB, $\hat{\alpha}$ estimates α well for α between 0 and 0.8 $\Delta\alpha$; and for input SNRs of 20 dB or greater, $\hat{\alpha}$ estimates α for α between 0 and $\Delta\alpha$. These results are shown clearly in Figure 17.

The estimate $\hat{\alpha}$ is not acceptable for large Doppler shifts (i.e., Doppler shifts > $\Delta\alpha$); therefore, this Doppler estimation/correction method may only be used for fine corrections of Doppler within a received signal baud and Doppler channel, where the maximum Doppler mismatch is $\pm\ \Delta\alpha/2$. Note from Figure 17 that the estimation is perfect for 0.5 $\Delta\alpha$.

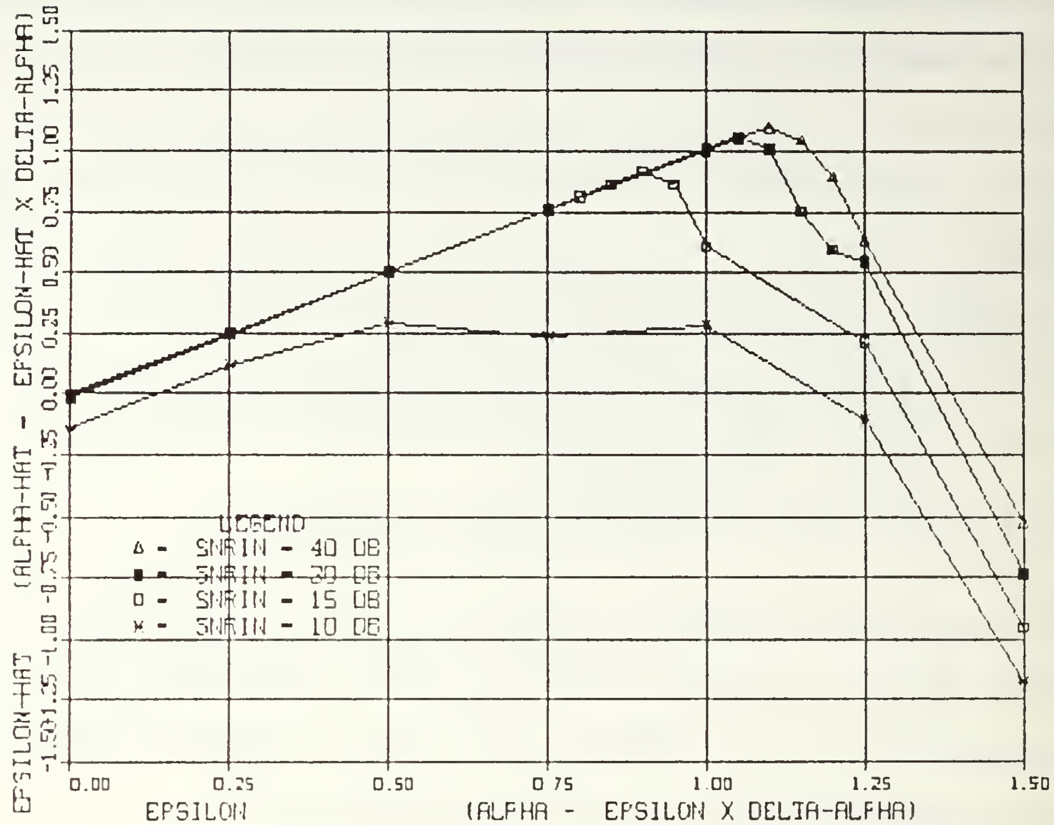


Figure 17. ALPHA-HAT vs. ALPHA for SNR_{IN} = 10, 15, 20, and 40 dB

VII. CONCLUSIONS AND RECOMMENDATIONS

A numerical code to simulate a MFQPSK signal received from a moving transmitter through a bandpass channel has been developed. It resides presently on the NPS IBM mainframe computer. The simulation is written in FORTRAN 77 and the code is included in Appendix F.

The model of the transmitter platform dynamics in the simulation is limited to straight line motion with random fluctuations. Actual transmitter platforms have motion in the pitch, yaw, and roll planes too and thus a six-degree-of-freedom model may be more realistic for future studies of platform motion effects on MFQPSK signalling.

The simulation should be tested further with actual test data to ensure that it produces a realistic received signal. Validation with actual test data may show that other channel characteristics or parameters which have not been considered in the simulation are important and must be included.

An important discovery of the simulation was that the output SNR degradation due to Doppler shift was primarily due to ISI. ISI cannot be neglected; therefore a theoretical analysis of ISI should be developed to realistically analyze MFQPSK in the presence of Doppler.

The Doppler estimation/correction method analyzed and presented in chapter VI only appears useful to remove small Doppler shifts (i.e., for fine adjustments only). Analysis of methods to remove larger Doppler shifts (i.e., coarse adjustments) across several bauds or a packet should be performed for MFQPSK signals.

Synchronization error estimation and correction has not yet been addressed with this simulation, but should be in the future.

This NPS developed MFQPSK signal has been implemented in hardware by T. Gantenbein and Dr. P. H. Moose using differential phase coding [Ref. 6]. It is conjectured that with differential coding the Doppler shifts, ISI, and synchronization errors will not affect the received signal as significantly as they affect the individually phase coded signal which is the coding technique presently implemented in the simulation. Therefore,the differential phase coding should be coded in the simulation. Doppler, ISI, and synchronization estimation/correction methods should be studied that are compatible with differential phase coding.

APPENDIX A

DERIVATION OF £(u)

Given the model of the channel's time delays below in Figure 18, assume x(u) is a superposition of N impulses;

$$x(u) = \sum_{i=1}^{N} A_i \ \delta(u-u_i) \quad . \tag{60}$$

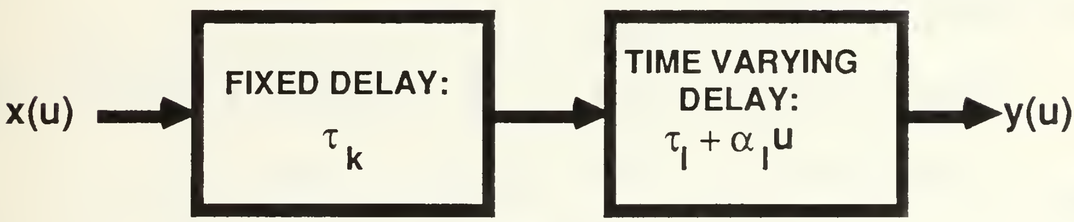


Figure 18. Time Delay Model of Channel

An impulse sent at time u = 0 arrives at y at time $\tau_k + \tau_l + \alpha_l\tau_k$. Therefore, the output signal from the channel $y(\tau_k + \tau_l + \alpha_l\tau_k)$ is the impulse x(0); that is, $y(\tau_k + \tau_l + \alpha_l\tau_k) = x(0)$. An impulse sent at time ΔT arrives at the output of the channel at time

$$\Delta T + \tau_k + \tau_l + \alpha_l(\Delta T + \tau_k). \tag{61}$$

Therefore, the output signal from the channel

$$y(\Delta T + \tau_k + \tau_l + \alpha_l(\Delta T + \tau_k)) \tag{62}$$

which is the impulse $x(\Delta T)$; is

$$y(\Delta T + \tau_k + \tau_l + \alpha_l(\Delta T + \tau_k)) = x(\Delta T) \quad . \tag{63}$$

Now letting

$$u = \Delta T + \tau_k + \tau_l + \alpha_l(\Delta T + \tau_k) \tag{64}$$

which can be rewritten as

$$u = \Delta T(1 + \alpha_l) + \tau_k(1 + \alpha_l) + \tau_l \ , \tag{65}$$

then solving for ΔT yields

$$\Delta T = ((u - \tau_l) / (1 + \alpha_l)) - \tau_k = u - \tau_k - ((\tau_l + \alpha_l u) / (1 + \alpha_l)). \tag{66}$$

Thus,

$$y(u) = x(\Delta T) = x(u - \tau_k - ((\tau_l + \alpha_l u) / (1 + \alpha_l))) \tag{67}$$

or

$$y(u) = x(u - \tau_k - \pounds(u)) \tag{68}$$

where

$$\pounds(u) = ((\tau_l + \alpha_l u) / (1 + \alpha_l)). \tag{69}$$

APPENDIX B. AN EXAMPLE OF A SIMULATION RUN

A. INPUT FROM THE SCREEN

```
PLEASE ENTER THE INITIAL POSITION  X0,Y0,Z0 (FT)
  OF THE RECEIVER RELATIVE TO THE TRANSMITTER ...
X0 =  -10.0000   Y0 =   20.0000   Z0 =  -6000.000

ENTER THE TRANSMITTER"S VELOCITY AVERAGE AND VARIANCE
  IN THE X, Y, Z-DIRECTIONS (FT/SEC) AND (FT/SEC)**2 ...
  (I.E.  VXAVG, VXVAR, VYAVG, VYVAR, VZAVG, VZVAR)
VXAVG =   2.00000000       VXVAR =  0.500000007E-01
VYAVG =   4.00000000       VYVAR =  0.499999896E-02
VZAVG =  0.000000000E+00   VZVAR =  0.249999994E-02

ENTER THE AVERAGE SPEED OF SOUND IN FT/SEC
  AND THE VARIANCE IN (FT/SEC)**2  ...
C0 =   5000.00000      CVAR =  0.000000000E+00

ENTER THE TRANSMITTER"S DOWN LINK TRANSMITTED
  HALF BEAM WIDTH ANGLE (DEG)  ...
THETA0 =   4.00000000

DO YOU WANT NORMALIZED AMPLITUDE FOR THE RECEIVED SIGNAL?
     PLEASE ENTER 1:YES OR 0:NO ...
IAMP =           1

ENTER THE # OF PACKETS IN THE TRANSMITTED SIGNAL ...
NPAKS =           2
```

```
THIS PROGRAM ENCODES A QPSK MULTIFREQUENCY SIGNAL.
  THE PHASES ARE SHOWN BELOW FOR ONE FREQUENCY ...


         *                   *
         2                   1



     _______________ _______________



         *                   *
         3                   4




SELECT ONE OF THE FOLLOWING METHODS FOR ENCODING
  THE PHASES FOR EACH FREQUENCY FOR EVERY BAUD
  WITHIN EACH PACKET ...

   ENTER ...
     1: THE PROGRAM RANDOMLY SELECTS ALL THE PHASES
          FOR ALL    2 PACKETS
     2: YOU INDIVIDUALLY SELECT THE PHASES
METHOD =           1


ENTER THE BAUD TYPE # CORRESPONDING TO THE FOLLOWING
  BAUD LENGTH FOR PACKET NUMBER:    1 ...

         1 : BAUD LENGTH (DELT) = 1/240 SECONDS
         2 : BAUD LENGTH (DELT) = 1/120 SECONDS
         3 : BAUD LENGTH (DELT) = 1/60 SECONDS
         4 : BAUD LENGTH (DELT) = 1/30 SECONDS
         5 : BAUD LENGTH (DELT) = 1/15 SECONDS
BDTYPE(1) =           1


ENTER THE NUMBER OF BAUDS IN PACKET NUMBER:    1 ...
NBAUDS(1) =           1


ENTER THE BAUD TYPE # CORRESPONDING TO THE FOLLOWING
  BAUD LENGTH FOR PACKET NUMBER:    2 ...

         1 : BAUD LENGTH (DELT) = 1/240 SECONDS
         2 : BAUD LENGTH (DELT) = 1/120 SECONDS
         3 : BAUD LENGTH (DELT) = 1/60 SECONDS
         4 : BAUD LENGTH (DELT) = 1/30 SECONDS
         5 : BAUD LENGTH (DELT) = 1/15 SECONDS
BDTYPE(2) =           2


ENTER THE NUMBER OF BAUDS IN PACKET NUMBER:    2 ...
NBAUDS(2) =           1
```

```
WOULD YOU LIKE THE DISCETE FOURIER TRANSFORM
  OF THE OUTPUT SIGNAL ?  (ENTER  1:YES OR 0:NO) ...
IDFT =             1


WOULD YOU LIKE THE DFT OUTPUT WINDOWED ?
  ENTER  1:YES OR 0:NO ...
IWNDOW =             1


PLEASE ENTER THE DESIRED INPUT WIDE BAND
   SIGNAL-TO-NOISE RATIO IN DB ....
SNRDB =    15.0000
```

B. LIST OUTPUT TO DISK FILE 30

```
 48
  LL        K      PHI(LL,K)    IPHI
  1        68       -0.785      4
  1        69        0.785      1
  1        70        0.785      1
  1        71        2.356      2
  1        72       -2.356      3
  1        73       -2.356      3
  1        74       -2.356      3
  1        75       -0.785      4
  1        76        2.356      2
  1        77       -0.785      4
  1        78        2.356      2
  1        79        0.785      1
  1        80       -0.785      4
  1        81        0.785      1
  1        82        0.785      1
  1        83       -2.356      3
  2       135       -0.785      4
  2       136       -2.356      3
  2       137       -2.356      3
  2       138        2.356      2
  2       139       -2.356      3
  2       140        2.356      2
  2       141       -0.785      4
  2       142       -0.785      4
  2       143        0.785      1
  2       144       -0.785      4
  2       145        2.356      2
  2       146       -0.785      4
  2       147        2.356      2
  2       148        0.785      1
  2       149        0.785      1
  2       150        0.785      1
  2       151       -2.356      3
  2       152       -0.785      4
  2       153       -0.785      4
  2       154        2.356      2
  2       155       -2.356      3
  2       156        2.356      2
  2       157        2.356      2
  2       158       -2.356      3
  2       159        2.356      2
  2       160        2.356      2
  2       161        0.785      1
  2       162        2.356      2
  2       163        2.356      2
  2       164       -2.356      3
  2       165       -2.356      3
  2       166        2.356      2
```

DFT INPUT DATA FOR BAUD # 1

N	REAL PART	IMAG PART
0	0.200484E+01	0.000000E+00
1	-.291531E+01	0.000000E+00
2	-.122278E+01	0.000000E+00
3	0.225909E+01	0.000000E+00
4	0.176306E+01	0.000000E+00
5	-.118927E+01	0.000000E+00
6	-.218088E-01	0.000000E+00
7	-.235837E+00	0.000000E+00
8	-.613874E+00	0.000000E+00
9	0.194238E+01	0.000000E+00
10	-.130624E+01	0.000000E+00
11	-.342880E+00	0.000000E+00
12	0.207660E+01	0.000000E+00
13	-.329895E+00	0.000000E+00
14	-.369812E+01	0.000000E+00
15	0.348756E+01	0.000000E+00
16	0.125413E+01	0.000000E+00
17	-.485057E+01	0.000000E+00
18	0.209897E+01	0.000000E+00
19	0.725176E+01	0.000000E+00
20	-.267107E+01	0.000000E+00
21	-.327209E+01	0.000000E+00
22	0.502687E+01	0.000000E+00
23	-.287833E+01	0.000000E+00
24	-.696552E+01	0.000000E+00
25	0.376308E+01	0.000000E+00
26	0.269107E+01	0.000000E+00
27	-.425671E+01	0.000000E+00
28	-.142092E+01	0.000000E+00
29	0.417586E+01	0.000000E+00
30	-.685801E+00	0.000000E+00
31	-.910082E-01	0.000000E+00
32	0.237153E+01	0.000000E+00
33	0.686129E+00	0.000000E+00
34	-.128562E+01	0.000000E+00
35	0.271385E+01	0.000000E+00
36	0.143204E+01	0.000000E+00
37	0.122637E+01	0.000000E+00
38	0.156954E+01	0.000000E+00
39	-.215876E+01	0.000000E+00
40	-.159364E+00	0.000000E+00
41	0.406544E+01	0.000000E+00
42	0.115762E+01	0.000000E+00
43	-.275345E+01	0.000000E+00
44	0.252170E+01	0.000000E+00
45	-.110620E+01	0.000000E+00
46	-.378736E+00	0.000000E+00
47	0.253587E+01	0.000000E+00
48	-.494904E+00	0.000000E+00
49	-.336829E+01	0.000000E+00
50	0.299053E+01	0.000000E+00
51	-.839522E+00	0.000000E+00
52	-.154595E+01	0.000000E+00
53	-.102779E+01	0.000000E+00
54	0.128035E+01	0.000000E+00
55	-.365980E+00	0.000000E+00
56	-.550354E+01	0.000000E+00
57	-.281839E+00	0.000000E+00
58	0.125277E+01	0.000000E+00
59	-.697582E+00	0.000000E+00
60	0.705833E+00	0.000000E+00
61	0.133619E+01	0.000000E+00
62	0.229186E+00	0.000000E+00
63	-.356922E+00	0.000000E+00
64	0.444179E+00	0.000000E+00

65	0.413470E+01	0.000000E+00
66	-.175258E+01	0.000000E+00
67	-.939483E+00	0.000000E+00
68	0.279167E+00	0.000000E+00
69	-.211374E+00	0.000000E+00
70	0.749620E+00	0.000000E+00
71	0.227079E+01	0.000000E+00
72	0.169964E+01	0.000000E+00
73	-.360312E+01	0.000000E+00
74	0.181549E+01	0.000000E+00
75	0.192265E+01	0.000000E+00
76	-.243610E+01	0.000000E+00
77	-.571788E+00	0.000000E+00
78	0.171358E+01	0.000000E+00
79	-.227510E+01	0.000000E+00
80	0.154184E+01	0.000000E+00
81	0.240438E+01	0.000000E+00
82	-.142191E+01	0.000000E+00
83	-.171134E+01	0.000000E+00
84	0.349656E+01	0.000000E+00
85	-.214113E+01	0.000000E+00
86	0.219070E+01	0.000000E+00
87	0.363189E+01	0.000000E+00
88	0.713565E+00	0.000000E+00
89	-.240271E+01	0.000000E+00
90	0.625637E+00	0.000000E+00
91	0.177416E+01	0.000000E+00
92	-.548617E+01	0.000000E+00
93	0.517214E+01	0.000000E+00
94	0.379215E+01	0.000000E+00
95	-.540784E+01	0.000000E+00
96	0.428047E+01	0.000000E+00
97	0.534627E+01	0.000000E+00
98	-.433480E+01	0.000000E+00
99	-.320334E+00	0.000000E+00
100	0.504450E+01	0.000000E+00
101	-.394868E+01	0.000000E+00
102	-.180450E+01	0.000000E+00
103	0.731280E+01	0.000000E+00
104	-.358992E+01	0.000000E+00
105	-.684641E+01	0.000000E+00
106	0.478245E+01	0.000000E+00
107	0.353709E+01	0.000000E+00
108	-.738240E+01	0.000000E+00
109	0.855238E+00	0.000000E+00
110	0.565053E+01	0.000000E+00
111	-.466334E+01	0.000000E+00
112	-.202646E+01	0.000000E+00
113	0.416927E+01	0.000000E+00
114	0.943901E+00	0.000000E+00
115	-.129343E+01	0.000000E+00
116	-.182671E+00	0.000000E+00
117	0.314196E+01	0.000000E+00
118	-.641427E+00	0.000000E+00
119	-.229205E+01	0.000000E+00
120	0.894737E-02	0.000000E+00
121	-.208729E+01	0.000000E+00
122	0.127476E+01	0.000000E+00
123	0.189270E+01	0.000000E+00
124	0.827031E+00	0.000000E+00
125	-.180424E+01	0.000000E+00
126	0.181878E-01	0.000000E+00
127	0.738333E+00	0.000000E+00
128	0.130366E+01	0.000000E+00
129	0.426684E+00	0.000000E+00
130	0.200011E+01	0.000000E+00
131	-.176676E+01	0.000000E+00
132	-.184777E+01	0.000000E+00
133	0.305751E+01	0.000000E+00
134	-.415754E+00	0.000000E+00
135	-.356674E+01	0.000000E+00
136	0.429929E+01	0.000000E+00

137	0.331470E+01	0.000000E+00
138	-.484753E+01	0.000000E+00
139	-.127909E+01	0.000000E+00
140	0.602902E+01	0.000000E+00
141	0.847187E-01	0.000000E+00
142	-.353355E+01	0.000000E+00
143	0.508767E+01	0.000000E+00
144	0.341302E+01	0.000000E+00
145	-.246052E+01	0.000000E+00
146	0.850205E+00	0.000000E+00
147	0.319615E+01	0.000000E+00
148	-.407688E+01	0.000000E+00
149	-.112038E+00	0.000000E+00
150	0.436206E+01	0.000000E+00
151	0.205910E+01	0.000000E+00
152	-.242958E+01	0.000000E+00
153	0.360312E+01	0.000000E+00
154	0.238491E+01	0.000000E+00
155	0.885219E+00	0.000000E+00
156	-.307407E+01	0.000000E+00
157	0.230542E+01	0.000000E+00
158	0.173215E+01	0.000000E+00
159	-.932735E+00	0.000000E+00
160	0.963823E+00	0.000000E+00
161	0.193234E+01	0.000000E+00
162	0.574894E-01	0.000000E+00
163	-.168030E+01	0.000000E+00
164	0.330895E+01	0.000000E+00
165	-.280785E+01	0.000000E+00
166	-.376674E+01	0.000000E+00
167	0.258334E+01	0.000000E+00
168	0.592477E+00	0.000000E+00
169	-.419450E+01	0.000000E+00
170	0.111468E+01	0.000000E+00
171	0.271280E+01	0.000000E+00
172	-.502696E+01	0.000000E+00
173	-.321339E+01	0.000000E+00
174	0.732952E+01	0.000000E+00
175	-.217458E+01	0.000000E+00
176	-.501133E+01	0.000000E+00
177	0.301020E+01	0.000000E+00
178	0.179601E+01	0.000000E+00
179	-.189239E+01	0.000000E+00
180	0.346009E+01	0.000000E+00
181	-.109089E+01	0.000000E+00
182	-.391839E+00	0.000000E+00
183	0.417718E+00	0.000000E+00
184	-.272576E+01	0.000000E+00
185	-.153335E+01	0.000000E+00
186	0.340410E+01	0.000000E+00
187	-.250186E+00	0.000000E+00
188	-.513401E+01	0.000000E+00
189	0.468323E+01	0.000000E+00
190	0.310899E+01	0.000000E+00
191	-.444465E+01	0.000000E+00
192	-.127312E+01	0.000000E+00
193	0.250906E+01	0.000000E+00
194	-.666324E+00	0.000000E+00
195	-.134897E+01	0.000000E+00
196	0.570884E+01	0.000000E+00
197	-.896835E-01	0.000000E+00
198	-.293430E+01	0.000000E+00
199	-.239388E+01	0.000000E+00
200	-.312660E+00	0.000000E+00
201	0.871717E+00	0.000000E+00
202	-.115026E+01	0.000000E+00
203	-.344144E+01	0.000000E+00
204	0.286601E+01	0.000000E+00
205	0.451813E+01	0.000000E+00
206	-.516409E+01	0.000000E+00
207	-.216182E+01	0.000000E+00
208	0.682289E+01	0.000000E+00

209	0.316336E+00	0.000000E+00
210	-.910015E+01	0.000000E+00
211	0.373189E+01	0.000000E+00
212	0.459230E+01	0.000000E+00
213	-.709038E+01	0.000000E+00
214	-.790167E-01	0.000000E+00
215	0.640498E+01	0.000000E+00
216	0.885365E+00	0.000000E+00
217	-.101914E+02	0.000000E+00
218	0.376423E+01	0.000000E+00
219	-.109551E+00	0.000000E+00
220	-.386085E+01	0.000000E+00
221	-.380749E+01	0.000000E+00
222	0.589190E+01	0.000000E+00
223	0.234406E+00	0.000000E+00
224	-.489929E+01	0.000000E+00
225	-.257231E+01	0.000000E+00
226	0.668187E+01	0.000000E+00
227	0.256053E+00	0.000000E+00
228	-.820556E+01	0.000000E+00
229	0.317285E+01	0.000000E+00
230	0.728581E+01	0.000000E+00
231	-.353177E+01	0.000000E+00
232	-.473028E+01	0.000000E+00
233	0.651311E+01	0.000000E+00
234	-.125509E+01	0.000000E+00
235	-.923538E+01	0.000000E+00
236	0.317662E+01	0.000000E+00
237	0.596793E+01	0.000000E+00
238	-.415065E+01	0.000000E+00
239	0.927513E+00	0.000000E+00
240	0.638412E+01	0.000000E+00
241	0.116869E+01	0.000000E+00
242	-.316552E+01	0.000000E+00
243	0.217262E+01	0.000000E+00
244	0.134112E+01	0.000000E+00
245	-.508769E+01	0.000000E+00
246	0.219943E+01	0.000000E+00
247	0.279915E+01	0.000000E+00
248	-.269927E+01	0.000000E+00
249	0.254480E+00	0.000000E+00
250	0.117177E+01	0.000000E+00
251	-.115213E+01	0.000000E+00
252	-.553449E+00	0.000000E+00
253	0.370947E+01	0.000000E+00
254	0.146894E+01	0.000000E+00
255	0.176158E+01	0.000000E+00

DFT OUTPUT DATA FOR BAUD # 1

K	REAL PART	IMAG PART	MAGNITUDE	PHASE (DEG)	PHASE (RAD)
68	0.90637344E+02	-.90041351E+02	0.12775980E+03	-.44811005E+02	-.78209955E+00
69	0.12512837E+03	0.87728928E+02	0.15281844E+03	0.35034729E+02	0.61147141E+00
70	0.85056396E+02	0.10223833E+03	0.13299347E+03	0.50241470E+02	0.87687898E+00
71	-.95022675E+02	0.10510611E+03	0.14169193E+03	0.13211565E+03	0.23058529E+01
72	-.80296448E+02	-.10472539E+03	0.13196561E+03	-.12747855E+03	-.22249212E+01
73	-.11772476E+03	-.10389015E+03	0.15701044E+03	-.13857214E+03	-.24185400E+01
74	-.10582492E+03	-.87098938E+02	0.13705887E+03	-.14054395E+03	-.24529552E+01
75	0.95074265E+02	-.11210881E+03	0.14699489E+03	-.49700256E+02	-.86743307E+00
76	-.73995346E+02	0.71338562E+02	0.10278374E+03	0.13604727E+03	0.23744726E+01
77	0.95286469E+02	-.91973923E+02	0.13243378E+03	-.43986572E+02	-.76771045E+00
78	-.75572342E+02	0.88835632E+02	0.11663167E+03	0.13038779E+03	0.22756958E+01
79	0.84246826E+02	0.97707855E+02	0.12901299E+03	0.49231018E+02	0.85924339E+00
80	0.11124681E+03	-.82108078E+02	0.13826636E+03	-.36429962E+02	-.63582295E+00
81	0.10516679E+03	0.83761368E+02	0.13444707E+03	0.38535995E+02	0.67257994E+00
82	0.11486154E+03	0.10973633E+03	0.15885600E+03	0.43692764E+02	0.76258266E+00
83	-.89434708E+02	-.95062195E+02	0.13051968E+03	-.13325296E+03	-.23257027E+01

NOTE: The DFT is windowed (IWNDOW = 1)

DFT INPUT DATA FOR BAUD # 2

N	REAL PART	IMAG PART
0	-.526725E+01	0.000000E+00
1	-.394182E+00	0.000000E+00
2	0.696870E+01	0.000000E+00
3	-.290471E+01	0.000000E+00
4	-.384541E+01	0.000000E+00
5	0.468083E+01	0.000000E+00
6	-.439102E+01	0.000000E+00
7	-.115464E+01	0.000000E+00
8	0.533558E+01	0.000000E+00
9	-.240291E+01	0.000000E+00
10	-.667564E+01	0.000000E+00
11	0.728867E+01	0.000000E+00
12	0.474582E+00	0.000000E+00
13	-.380783E+01	0.000000E+00
14	0.311805E+01	0.000000E+00
15	0.450043E+01	0.000000E+00
16	-.446419E+01	0.000000E+00
17	0.199608E+01	0.000000E+00
18	0.185680E+01	0.000000E+00
19	-.970748E+01	0.000000E+00
20	0.440136E+01	0.000000E+00
21	0.601283E+01	0.000000E+00
22	-.750463E+01	0.000000E+00
23	-.344410E+01	0.000000E+00
24	0.110174E+02	0.000000E+00
25	0.249212E+01	0.000000E+00
26	-.811214E+01	0.000000E+00
27	0.863213E+01	0.000000E+00
28	0.576661E+01	0.000000E+00
29	-.834345E+01	0.000000E+00
30	-.330458E+01	0.000000E+00
31	0.113159E+02	0.000000E+00
32	0.149053E+01	0.000000E+00
33	-.194054E+01	0.000000E+00
34	0.498989E+01	0.000000E+00
35	0.492170E+01	0.000000E+00
36	-.811450E+01	0.000000E+00
37	0.138805E+01	0.000000E+00
38	0.412452E+01	0.000000E+00
39	-.386714E+01	0.000000E+00
40	-.588585E+01	0.000000E+00
41	0.650927E+01	0.000000E+00
42	0.396164E+00	0.000000E+00
43	0.101974E+00	0.000000E+00
44	0.422124E+01	0.000000E+00
45	-.261774E+01	0.000000E+00
46	-.652925E+01	0.000000E+00
47	0.692594E+01	0.000000E+00
48	0.912038E+00	0.000000E+00
49	-.929524E+01	0.000000E+00
50	0.202819E+01	0.000000E+00
51	0.106854E+02	0.000000E+00
52	-.710419E+01	0.000000E+00
53	-.457107E+01	0.000000E+00
54	0.104375E+02	0.000000E+00
55	-.104101E+01	0.000000E+00
56	-.712630E+01	0.000000E+00
57	0.622043E+01	0.000000E+00
58	0.965949E+01	0.000000E+00
59	-.112449E+02	0.000000E+00
60	-.477618E+01	0.000000E+00
61	0.101622E+02	0.000000E+00
62	0.207549E+01	0.000000E+00
63	-.460409E+01	0.000000E+00
64	0.214426E+01	0.000000E+00
65	0.406143E+01	0.000000E+00

66	-.242523E+01	0.000000E+00
67	-.426298E+01	0.000000E+00
68	-.407959E+00	0.000000E+00
69	0.548756E+01	0.000000E+00
70	-.242346E+01	0.000000E+00
71	-.285746E+01	0.000000E+00
72	0.931297E+01	0.000000E+00
73	0.285819E+01	0.000000E+00
74	-.899141E+01	0.000000E+00
75	0.387245E+00	0.000000E+00
76	0.578286E+01	0.000000E+00
77	-.490578E+01	0.000000E+00
78	-.144855E+00	0.000000E+00
79	0.642747E+01	0.000000E+00
80	0.213817E+00	0.000000E+00
81	-.223994E+01	0.000000E+00
82	0.170248E+01	0.000000E+00
83	-.325185E+00	0.000000E+00
84	-.174552E+01	0.000000E+00
85	0.526715E+00	0.000000E+00
86	-.176461E+01	0.000000E+00
87	-.392745E+01	0.000000E+00
88	0.614061E+01	0.000000E+00
89	-.354380E+00	0.000000E+00
90	-.750051E+01	0.000000E+00
91	0.551929E+01	0.000000E+00
92	0.380251E+01	0.000000E+00
93	-.484067E+01	0.000000E+00
94	-.182470E+01	0.000000E+00
95	0.584987E+01	0.000000E+00
96	-.323802E+01	0.000000E+00
97	-.358901E+01	0.000000E+00
98	0.548582E+01	0.000000E+00
99	0.277453E+01	0.000000E+00
100	-.177448E+01	0.000000E+00
101	-.301150E+00	0.000000E+00
102	0.494978E+00	0.000000E+00
103	0.216534E+01	0.000000E+00
104	-.216204E+01	0.000000E+00
105	-.329386E+01	0.000000E+00
106	-.238950E+01	0.000000E+00
107	0.349077E+01	0.000000E+00
108	-.454049E+01	0.000000E+00
109	-.237934E+00	0.000000E+00
110	0.778620E+01	0.000000E+00
111	0.125057E+01	0.000000E+00
112	-.132939E+01	0.000000E+00
113	-.121500E+01	0.000000E+00
114	0.302725E+01	0.000000E+00
115	-.207522E+01	0.000000E+00
116	-.233488E+01	0.000000E+00
117	0.142058E+01	0.000000E+00
118	-.349241E+00	0.000000E+00
119	-.429151E+01	0.000000E+00
120	0.323071E+01	0.000000E+00
121	0.584821E+00	0.000000E+00
122	-.693258E+00	0.000000E+00
123	-.275253E+01	0.000000E+00
124	0.208057E+01	0.000000E+00
125	0.542997E+00	0.000000E+00
126	-.197652E+01	0.000000E+00
127	-.154319E+01	0.000000E+00
128	-.420868E+01	0.000000E+00
129	-.113642E+01	0.000000E+00
130	-.201206E+01	0.000000E+00
131	0.105195E+01	0.000000E+00
132	-.264909E+01	0.000000E+00
133	-.401588E+00	0.000000E+00
134	0.531781E+01	0.000000E+00
135	-.470942E+01	0.000000E+00
136	-.477054E+01	0.000000E+00
137	0.643067E+01	0.000000E+00

138	-.110850E+01	0.000000E+00
139	-.466090E+01	0.000000E+00
140	0.382527E+01	0.000000E+00
141	0.389133E+01	0.000000E+00
142	-.508665E+01	0.000000E+00
143	0.366893E+01	0.000000E+00
144	0.604237E+01	0.000000E+00
145	-.266780E+01	0.000000E+00
146	-.120114E+01	0.000000E+00
147	0.394714E+01	0.000000E+00
148	-.545985E-01	0.000000E+00
149	-.313556E+01	0.000000E+00
150	-.733842E+00	0.000000E+00
151	-.177183E-01	0.000000E+00
152	-.281948E+00	0.000000E+00
153	0.643579E+01	0.000000E+00
154	-.231300E+01	0.000000E+00
155	-.248661E+01	0.000000E+00
156	0.441114E+01	0.000000E+00
157	-.283533E+01	0.000000E+00
158	-.626540E+01	0.000000E+00
159	0.582976E+01	0.000000E+00
160	0.176179E+00	0.000000E+00
161	-.254206E+01	0.000000E+00
162	0.552283E+00	0.000000E+00
163	0.443619E+01	0.000000E+00
164	-.811100E+00	0.000000E+00
165	0.614064E+00	0.000000E+00
166	0.348493E+01	0.000000E+00
167	-.542510E+01	0.000000E+00
168	-.285739E+00	0.000000E+00
169	-.908447E+00	0.000000E+00
170	-.758899E+01	0.000000E+00
171	0.872746E+00	0.000000E+00
172	0.510780E+01	0.000000E+00
173	-.642361E+01	0.000000E+00
174	-.196627E+01	0.000000E+00
175	0.604545E+01	0.000000E+00
176	-.406701E+01	0.000000E+00
177	-.907386E+01	0.000000E+00
178	0.522828E+01	0.000000E+00
179	0.274564E+01	0.000000E+00
180	-.836539E+01	0.000000E+00
181	0.758526E+00	0.000000E+00
182	0.555079E+01	0.000000E+00
183	-.524344E+00	0.000000E+00
184	-.604758E+01	0.000000E+00
185	0.451275E+01	0.000000E+00
186	0.691295E+00	0.000000E+00
187	-.408368E+01	0.000000E+00
188	-.421285E+01	0.000000E+00
189	0.297227E+01	0.000000E+00
190	0.138190E+01	0.000000E+00
191	-.497323E+01	0.000000E+00
192	0.272180E+01	0.000000E+00
193	0.999976E+00	0.000000E+00
194	-.198997E+01	0.000000E+00
195	-.321780E+01	0.000000E+00
196	0.117637E+01	0.000000E+00
197	0.322415E+01	0.000000E+00
198	-.458584E+01	0.000000E+00
199	-.421095E+01	0.000000E+00
200	0.435145E+01	0.000000E+00
201	-.580684E+00	0.000000E+00
202	-.501254E+01	0.000000E+00
203	0.115667E+01	0.000000E+00
204	-.203047E+00	0.000000E+00
205	-.292859E+01	0.000000E+00
206	-.315172E+01	0.000000E+00
207	0.280452E+01	0.000000E+00
208	0.373484E+01	0.000000E+00
209	-.424158E+01	0.000000E+00

210	-.262466E+01	0.000000E+00
211	0.494710E+01	0.000000E+00
212	-.142531E+01	0.000000E+00
213	-.941097E+01	0.000000E+00
214	0.318101E+01	0.000000E+00
215	0.424388E+01	0.000000E+00
216	-.650536E+01	0.000000E+00
217	-.124455E+01	0.000000E+00
218	0.738448E+01	0.000000E+00
219	-.604091E+01	0.000000E+00
220	-.656762E+01	0.000000E+00
221	0.350399E+01	0.000000E+00
222	0.608059E+01	0.000000E+00
223	-.523418E+01	0.000000E+00
224	-.253131E+01	0.000000E+00
225	0.883400E+01	0.000000E+00
226	-.569328E+01	0.000000E+00
227	-.112117E+02	0.000000E+00
228	0.645991E+01	0.000000E+00
229	0.547792E+01	0.000000E+00
230	-.782587E+01	0.000000E+00
231	-.427295E+01	0.000000E+00
232	0.980781E+01	0.000000E+00
233	-.190006E+01	0.000000E+00
234	-.471819E+01	0.000000E+00
235	0.728085E+01	0.000000E+00
236	0.314933E+01	0.000000E+00
237	-.106632E+02	0.000000E+00
238	0.194443E+01	0.000000E+00
239	0.765045E+01	0.000000E+00
240	-.357001E+01	0.000000E+00
241	-.640628E+00	0.000000E+00
242	0.354356E+01	0.000000E+00
243	0.182806E+01	0.000000E+00
244	-.669535E+00	0.000000E+00
245	-.275834E+01	0.000000E+00
246	0.240171E+01	0.000000E+00
247	-.151564E+01	0.000000E+00
248	-.253017E+01	0.000000E+00
249	-.379693E+00	0.000000E+00
250	0.388394E+01	0.000000E+00
251	-.289334E+01	0.000000E+00
252	0.214223E+00	0.000000E+00
253	-.294030E+01	0.000000E+00
254	0.413015E+00	0.000000E+00
255	0.353020E+01	0.000000E+00
256	0.116558E+01	0.000000E+00
257	-.362289E+00	0.000000E+00
258	-.386072E+01	0.000000E+00
259	-.129466E+01	0.000000E+00
260	0.532838E+00	0.000000E+00
261	0.584236E+00	0.000000E+00
262	-.339053E+01	0.000000E+00
263	0.256464E+01	0.000000E+00
264	0.152053E+01	0.000000E+00
265	-.475879E+01	0.000000E+00
266	0.368118E+01	0.000000E+00
267	-.267406E+00	0.000000E+00
268	-.466596E+01	0.000000E+00
269	-.184211E+01	0.000000E+00
270	0.400506E+01	0.000000E+00
271	-.452730E+01	0.000000E+00
272	-.526406E+01	0.000000E+00
273	0.578228E+01	0.000000E+00
274	0.348354E+01	0.000000E+00
275	-.493828E+01	0.000000E+00
276	-.308919E+01	0.000000E+00
277	0.871899E+01	0.000000E+00
278	0.399700E+00	0.000000E+00
279	-.538871E+01	0.000000E+00
280	0.156540E+01	0.000000E+00
281	0.289917E+01	0.000000E+00

282	0.650645E-01	0.000000E+00
283	-.374218E+01	0.000000E+00
284	0.392436E+01	0.000000E+00
285	0.753166E+01	0.000000E+00
286	-.239218E+01	0.000000E+00
287	-.625107E+01	0.000000E+00
288	0.464018E+01	0.000000E+00
289	0.803769E+01	0.000000E+00
290	-.486152E+01	0.000000E+00
291	-.450123E+01	0.000000E+00
292	0.736135E+01	0.000000E+00
293	-.191086E+01	0.000000E+00
294	-.418490E+01	0.000000E+00
295	0.810541E+01	0.000000E+00
296	0.481734E+01	0.000000E+00
297	-.821385E+01	0.000000E+00
298	-.678597E+00	0.000000E+00
299	0.493847E+01	0.000000E+00
300	-.376643E+01	0.000000E+00
301	-.355329E+01	0.000000E+00
302	0.366560E+01	0.000000E+00
303	0.115503E+01	0.000000E+00
304	-.399879E+01	0.000000E+00
305	0.126453E+01	0.000000E+00
306	0.735960E+01	0.000000E+00
307	-.381905E+01	0.000000E+00
308	-.238577E+01	0.000000E+00
309	0.122439E+01	0.000000E+00
310	0.642341E+00	0.000000E+00
311	-.115598E+01	0.000000E+00
312	0.284103E+01	0.000000E+00
313	0.501446E+00	0.000000E+00
314	0.177095E+01	0.000000E+00
315	0.128382E+01	0.000000E+00
316	-.779019E+01	0.000000E+00
317	0.361360E+01	0.000000E+00
318	0.235632E+01	0.000000E+00
319	-.544813E+00	0.000000E+00
320	-.177875E+01	0.000000E+00
321	0.902049E+00	0.000000E+00
322	0.172862E+01	0.000000E+00
323	-.228558E+01	0.000000E+00
324	0.150589E+01	0.000000E+00
325	0.379671E+01	0.000000E+00
326	-.367524E+01	0.000000E+00
327	0.321874E+01	0.000000E+00
328	0.288017E+01	0.000000E+00
329	0.122940E+01	0.000000E+00
330	0.290588E+01	0.000000E+00
331	0.193080E+01	0.000000E+00
332	0.259495E-02	0.000000E+00
333	-.331905E+01	0.000000E+00
334	0.732367E+01	0.000000E+00
335	-.264367E+01	0.000000E+00
336	-.805418E+01	0.000000E+00
337	0.289561E+01	0.000000E+00
338	0.549653E+01	0.000000E+00
339	-.565418E+01	0.000000E+00
340	-.205987E+01	0.000000E+00
341	0.556493E+01	0.000000E+00
342	-.594744E+01	0.000000E+00
343	-.371291E+01	0.000000E+00
344	0.430186E+01	0.000000E+00
345	0.409844E+00	0.000000E+00
346	-.677720E+01	0.000000E+00
347	0.455239E+01	0.000000E+00
348	0.546079E+01	0.000000E+00
349	-.594345E+01	0.000000E+00
350	-.872316E+00	0.000000E+00
351	0.585900E+01	0.000000E+00
352	-.262263E+01	0.000000E+00
353	-.573845E+01	0.000000E+00

354	0.433496E+01	0.000000E+00
355	-.593394E+00	0.000000E+00
356	-.681707E+01	0.000000E+00
357	0.652774E+01	0.000000E+00
358	0.150886E+01	0.000000E+00
359	-.614447E+01	0.000000E+00
360	0.239488E+01	0.000000E+00
361	0.226228E+01	0.000000E+00
362	-.481258E+01	0.000000E+00
363	-.354793E+01	0.000000E+00
364	0.451782E+01	0.000000E+00
365	-.756871E+00	0.000000E+00
366	-.148307E+01	0.000000E+00
367	0.335441E+01	0.000000E+00
368	0.871370E+00	0.000000E+00
369	0.123139E+01	0.000000E+00
370	-.170679E+01	0.000000E+00
371	0.252001E+01	0.000000E+00
372	-.361835E+00	0.000000E+00
373	-.495687E+01	0.000000E+00
374	0.162119E+01	0.000000E+00
375	0.185459E+01	0.000000E+00
376	-.309277E+01	0.000000E+00
377	-.320235E+01	0.000000E+00
378	0.138036E+01	0.000000E+00
379	-.292664E+01	0.000000E+00
380	-.307330E+01	0.000000E+00
381	0.156635E+01	0.000000E+00
382	0.748866E+01	0.000000E+00
383	-.562336E+01	0.000000E+00
384	0.100312E+00	0.000000E+00
385	0.132461E+01	0.000000E+00
386	-.355028E+01	0.000000E+00
387	-.232426E+01	0.000000E+00
388	0.451112E+01	0.000000E+00
389	-.531282E+00	0.000000E+00
390	-.288922E+01	0.000000E+00
391	0.354156E+01	0.000000E+00
392	-.109373E+01	0.000000E+00
393	-.283108E+01	0.000000E+00
394	0.396496E+01	0.000000E+00
395	-.698274E+00	0.000000E+00
396	-.531781E+01	0.000000E+00
397	0.843346E+00	0.000000E+00
398	0.356507E+01	0.000000E+00
399	-.822237E+00	0.000000E+00
400	-.128205E+01	0.000000E+00
401	0.401342E+01	0.000000E+00
402	-.109053E+00	0.000000E+00
403	-.560845E+01	0.000000E+00
404	0.179668E+01	0.000000E+00
405	-.377383E+01	0.000000E+00
406	-.398152E+01	0.000000E+00
407	-.198354E+01	0.000000E+00
408	0.325370E+01	0.000000E+00
409	-.542649E+01	0.000000E+00
410	-.373510E+01	0.000000E+00
411	0.380313E+01	0.000000E+00
412	0.116460E+01	0.000000E+00
413	-.330263E+01	0.000000E+00
414	-.428371E+01	0.000000E+00
415	0.166203E+01	0.000000E+00
416	0.294798E+01	0.000000E+00
417	-.260710E+01	0.000000E+00
418	0.193795E+01	0.000000E+00
419	0.609513E+01	0.000000E+00
420	-.514264E+01	0.000000E+00
421	-.528953E+01	0.000000E+00
422	0.720675E+01	0.000000E+00
423	-.123952E+01	0.000000E+00
424	-.733272E+01	0.000000E+00
425	0.468533E+01	0.000000E+00

426	0.573544E+01	0.000000E+00
427	-.845249E+01	0.000000E+00
428	0.516992E+00	0.000000E+00
429	0.119343E+02	0.000000E+00
430	-.442223E+01	0.000000E+00
431	-.389617E+01	0.000000E+00
432	0.306069E+01	0.000000E+00
433	-.741859E+00	0.000000E+00
434	-.601171E+01	0.000000E+00
435	0.915210E+00	0.000000E+00
436	-.662840E+00	0.000000E+00
437	-.279501E+01	0.000000E+00
438	0.102183E+01	0.000000E+00
439	0.129399E+01	0.000000E+00
440	0.942253E+00	0.000000E+00
441	-.105543E+00	0.000000E+00
442	0.422624E+01	0.000000E+00
443	-.604331E+00	0.000000E+00
444	-.160753E+01	0.000000E+00
445	0.489188E+00	0.000000E+00
446	-.570710E+01	0.000000E+00
447	-.202896E+01	0.000000E+00
448	0.476189E+01	0.000000E+00
449	-.340101E+01	0.000000E+00
450	-.482951E+01	0.000000E+00
451	0.849652E+01	0.000000E+00
452	0.419645E+01	0.000000E+00
453	-.520679E+01	0.000000E+00
454	0.318501E+01	0.000000E+00
455	0.661741E+01	0.000000E+00
456	-.298308E+01	0.000000E+00
457	-.549945E+00	0.000000E+00
458	0.337600E+01	0.000000E+00
459	-.188377E+01	0.000000E+00
460	-.153699E+01	0.000000E+00
461	0.728273E+00	0.000000E+00
462	0.173535E+01	0.000000E+00
463	0.842127E-01	0.000000E+00
464	-.321595E+01	0.000000E+00
465	0.280456E+01	0.000000E+00
466	0.515843E+01	0.000000E+00
467	0.127567E+01	0.000000E+00
468	-.271868E+01	0.000000E+00
469	0.314677E+01	0.000000E+00
470	-.684675E+00	0.000000E+00
471	-.370720E+01	0.000000E+00
472	0.485160E+00	0.000000E+00
473	0.458457E+01	0.000000E+00
474	-.628002E+01	0.000000E+00
475	-.598999E+01	0.000000E+00
476	0.536761E+01	0.000000E+00
477	-.155600E+01	0.000000E+00
478	-.832894E+01	0.000000E+00
479	0.648226E+00	0.000000E+00
480	0.308144E+01	0.000000E+00
481	-.259356E+01	0.000000E+00
482	0.101954E+01	0.000000E+00
483	-.183804E+00	0.000000E+00
484	0.914496E+00	0.000000E+00
485	0.103868E+00	0.000000E+00
486	-.548742E+01	0.000000E+00
487	-.193591E+01	0.000000E+00
488	0.333655E+01	0.000000E+00
489	-.407597E+01	0.000000E+00
490	-.881921E+01	0.000000E+00
491	0.956705E+01	0.000000E+00
492	0.924545E+00	0.000000E+00
493	-.905340E+01	0.000000E+00
494	0.402092E+01	0.000000E+00
495	0.527295E+01	0.000000E+00
496	-.906265E+01	0.000000E+00
497	-.233179E+01	0.000000E+00

498	0.880906E+01	0.000000E+00
499	-.545897E+01	0.000000E+00
500	-.745451E+01	0.000000E+00
501	0.784850E+01	0.000000E+00
502	0.331564E+01	0.000000E+00
503	-.686388E+01	0.000000E+00
504	0.161638E+01	0.000000E+00
505	0.279832E+01	0.000000E+00
506	-.107526E+02	0.000000E+00
507	0.452893E+01	0.000000E+00
508	0.396753E+01	0.000000E+00
509	-.574705E+01	0.000000E+00
510	0.397997E+01	0.000000E+00
511	0.242562E+01	0.000000E+00

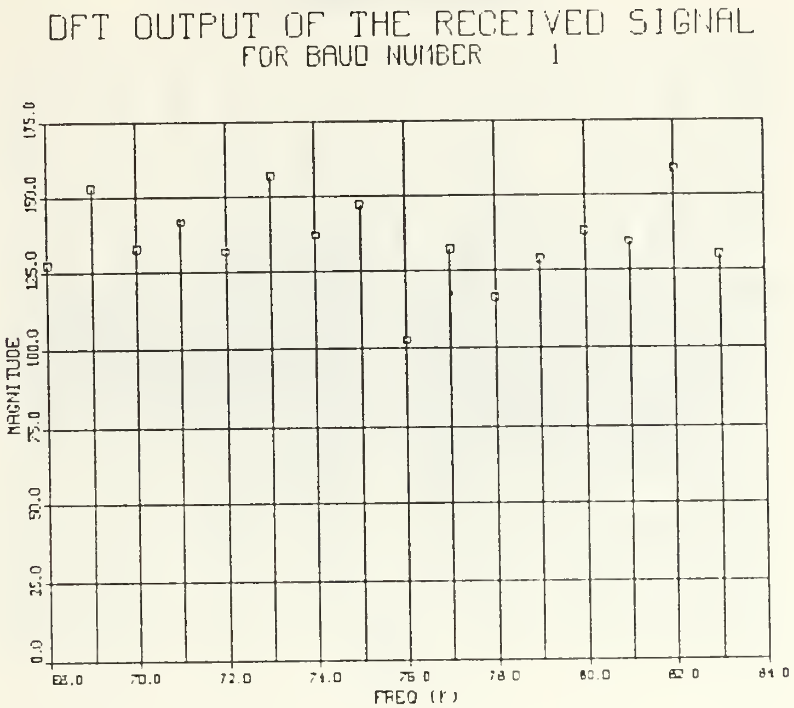
DFT OUTPUT DATA FOR BAUD # 2

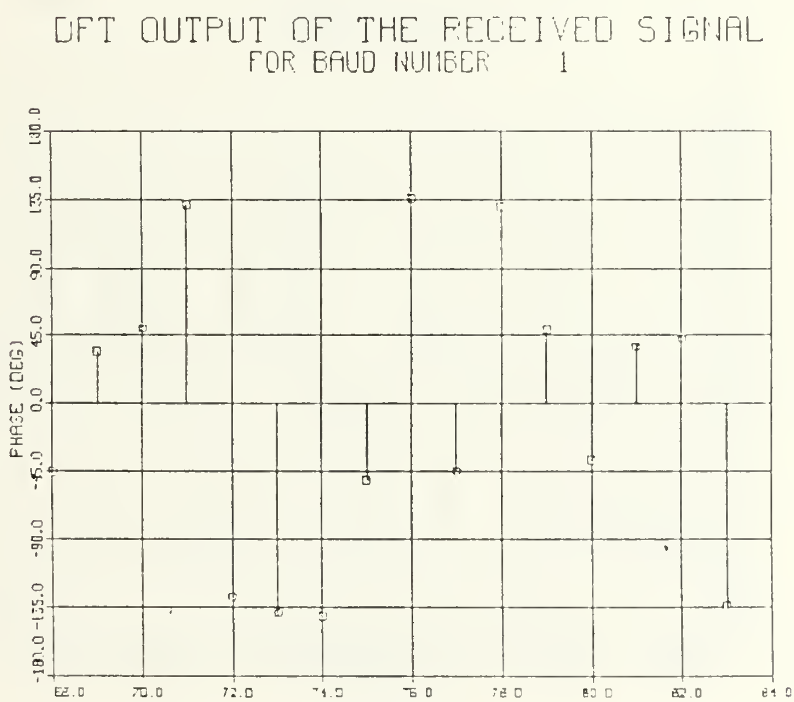
K	REAL PART	IMAG PART	MAGNITUDE	PHASE (DEG)	PHASE (RAD)
135	0.21869614E+03	-.13437286E+03	0.25667896E+03	-.31567688E+02	-.55096024E+00
136	-.20494591E+03	-.20220082E+03	0.28790259E+03	-.13538632E+03	-.23629370E+01
137	-.14575168E+03	-.15294678E+03	0.21127296E+03	-.13362015E+03	-.23321114E+01
138	-.21255940E+03	0.19105444E+03	0.28580273E+03	0.13804984E+03	0.24094248E+01
139	-.15577037E+03	-.13739233E+03	0.20770425E+03	-.13858707E+03	-.24188013E+01
140	-.13250822E+03	0.14138666E+03	0.19377464E+03	0.13314339E+03	0.23237906E+01
141	0.17392702E+03	-.22279741E+03	0.28264697E+03	-.52022568E+02	-.90796512E+00
142	0.13896306E+03	-.13225531E+03	0.19183899E+03	-.43583252E+02	-.76067126E+00
143	0.16901073E+03	0.14665094E+03	0.22376578E+03	0.40948242E+02	0.71468163E+00
144	0.19780035E+03	-.15818835E+03	0.25327560E+03	-.38650635E+02	-.67458087E+00
145	-.20230388E+03	0.27242383E+03	0.33932495E+03	0.12659782E+03	0.22095499E+01
146	0.20827090E+03	-.18137456E+03	0.27617651E+03	-.41051254E+02	-.71647972E+00
147	-.19098985E+03	0.22640436E+03	0.29620264E+03	0.13015030E+03	0.22715511E+01
148	0.15571500E+03	0.14765985E+03	0.21459401E+03	0.43479050E+02	0.75885254E+00
149	0.22490648E+03	0.18650417E+03	0.29217578E+03	0.39667282E+02	0.69232482E+00
150	0.18717580E+03	0.16107140E+03	0.24693880E+03	0.40713165E+02	0.71057868E+00
151	-.13020734E+03	-.21927161E+03	0.25501762E+03	-.12070264E+03	-.21066589E+01
152	0.21125522E+03	-.22968059E+03	0.31206079E+03	-.47392807E+02	-.82716048E+00
153	0.16326271E+03	-.17587959E+03	0.23997571E+03	-.47130524E+02	-.82258284E+00
154	-.18001019E+03	0.15380461E+03	0.23676892E+03	0.13948868E+03	0.24345369E+01
155	-.19258081E+03	-.13529289E+03	0.23535405E+03	-.14491098E+03	-.25291739E+01
156	-.19027963E+03	0.16097487E+03	0.24923732E+03	0.13976907E+03	0.24394302E+01
157	-.21412985E+03	0.18872530E+03	0.28542749E+03	0.13860835E+03	0.24191723E+01
158	-.20541913E+03	-.22383812E+03	0.30381006E+03	-.13254298E+03	-.23133116E+01
159	-.19955086E+03	0.20583072E+03	0.28668237E+03	0.13411246E+03	0.23407049E+01
160	-.21075299E+03	0.22362857E+03	0.30728906E+03	0.13330223E+03	0.23265629E+01
161	0.17198572E+03	0.17881973E+03	0.24810397E+03	0.46116013E+02	0.80487633E+00
162	-.17657683E+03	0.15956850E+03	0.23799471E+03	0.13789659E+03	0.24067497E+01
163	-.18814537E+03	0.14442966E+03	0.23718896E+03	0.14248830E+03	0.24868908E+01
164	-.17734966E+03	-.17915202E+03	0.25208797E+03	-.13471030E+03	-.23511391E+01
165	-.18872591E+03	-.18354022E+03	0.26325732E+03	-.13579803E+03	-.23701239E+01
166	-.18190575E+03	0.12815350E+03	0.22251521E+03	0.14483507E+03	0.25278492E+01

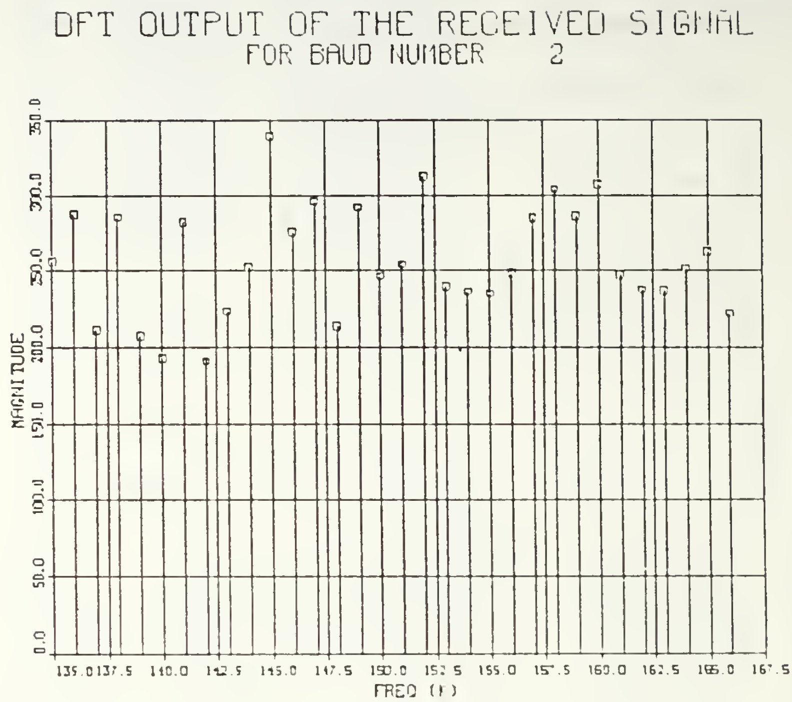
NOTE: The DFT is windowed (IWNDOW = 1)

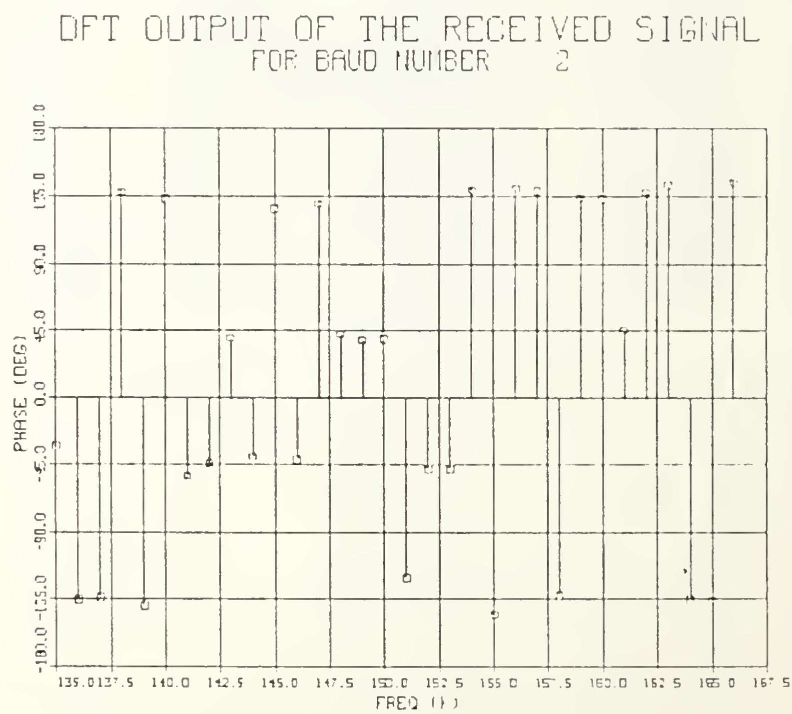
C. GRAPHICAL OUTPUT USING DISSPLA

1. DFT Windowed Between k_1 and k_2 (IWNDOW=1)

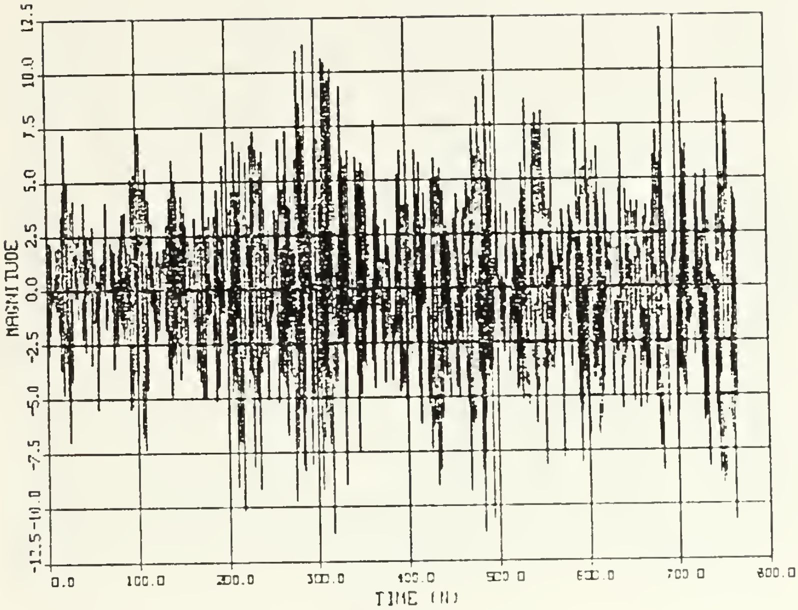




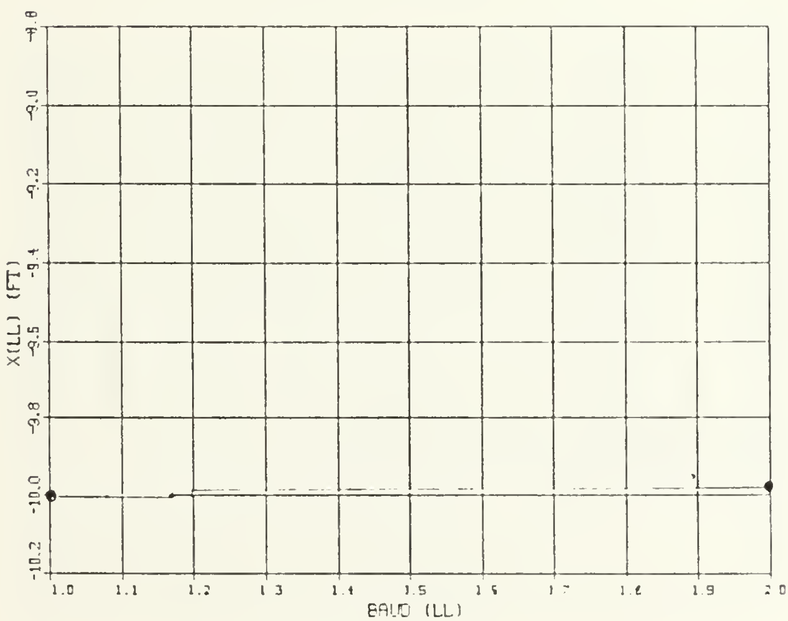

DFT OUTPUT OF THE RECEIVED SIGNAL
FOR BAUD NUMBER 2
MAGNITUDE
FREQ (F)

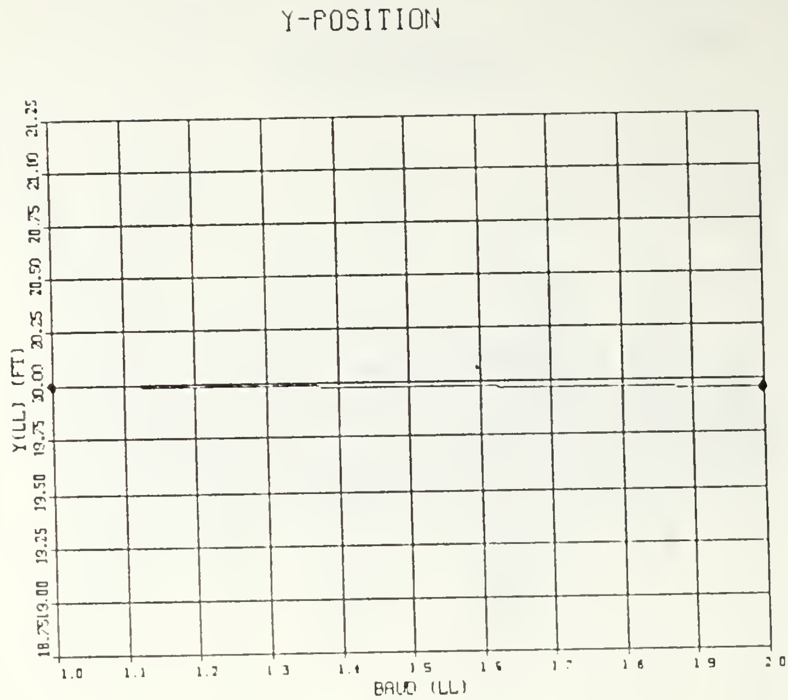

DFT OUTPUT OF THE RECEIVED SIGNAL
FOR BAUD NUMBER 2
PHASE (DEG)
FREQ (F)

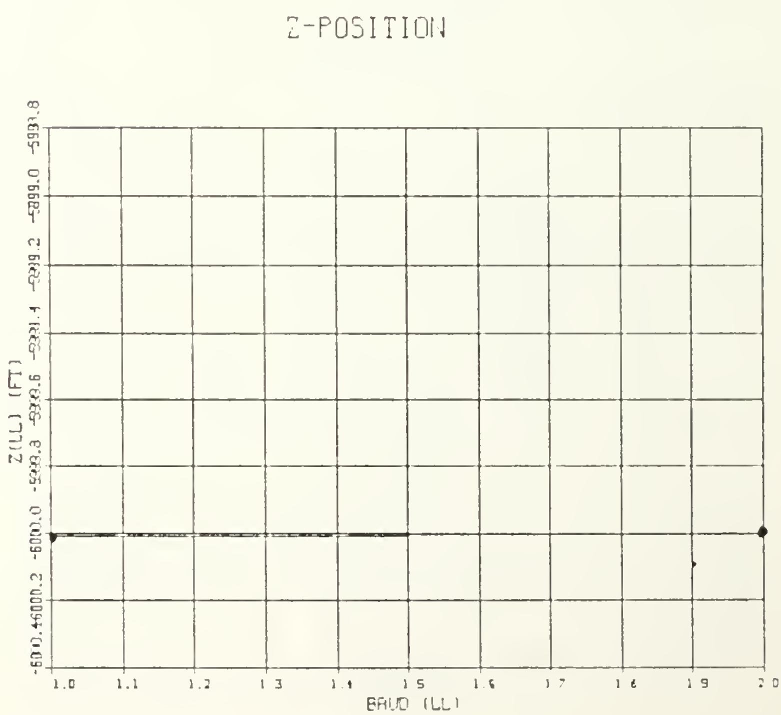
RECEIVED SIGNAL



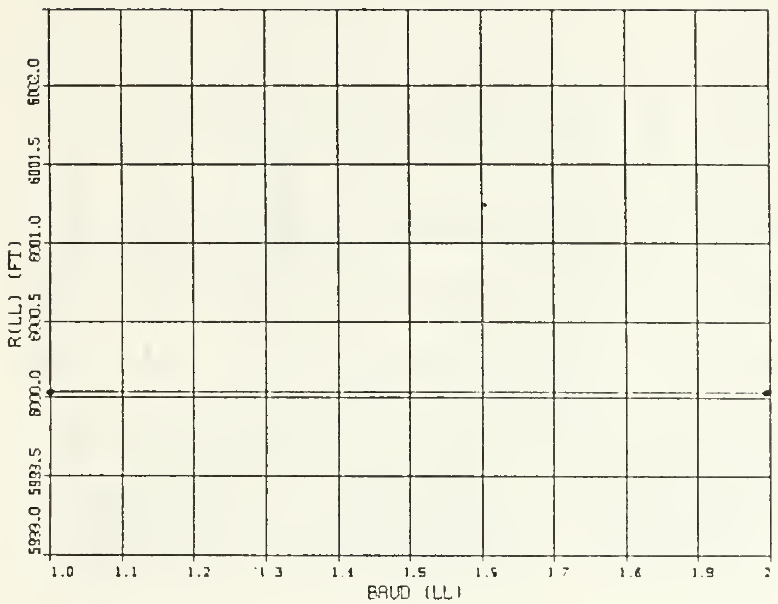
X-POSITION



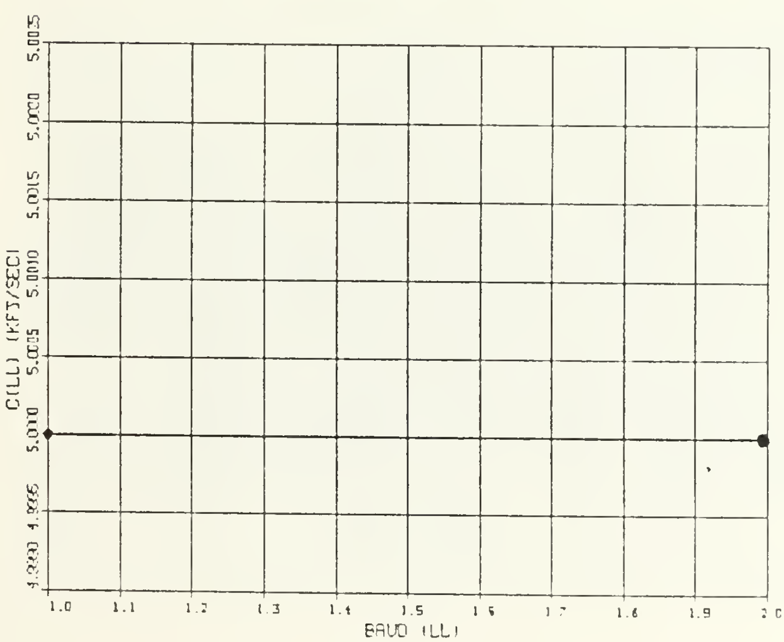

Y-POSITION
Y(LL) (FT)
BAUD (LL)

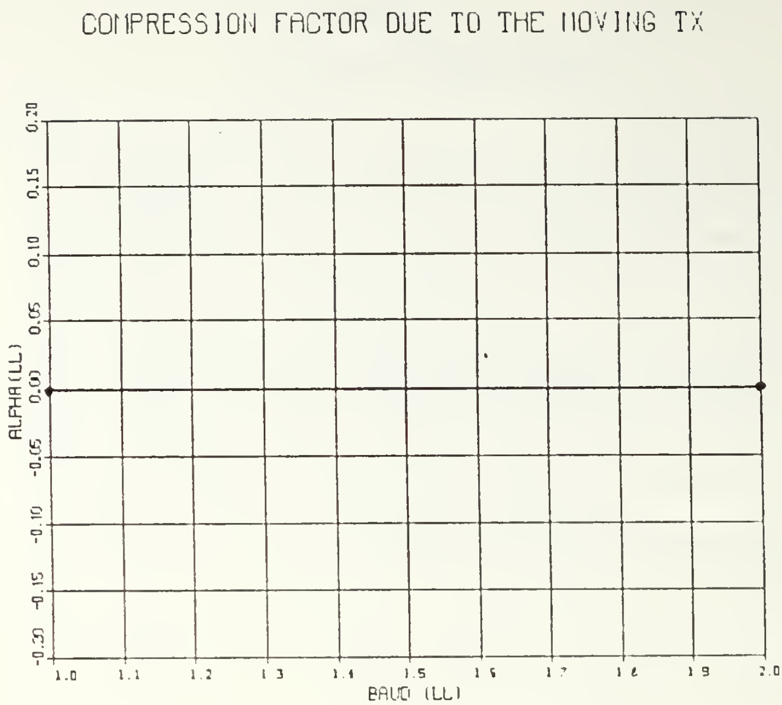

Z-POSITION
Z(LL) (FT)
BAUD (LL)

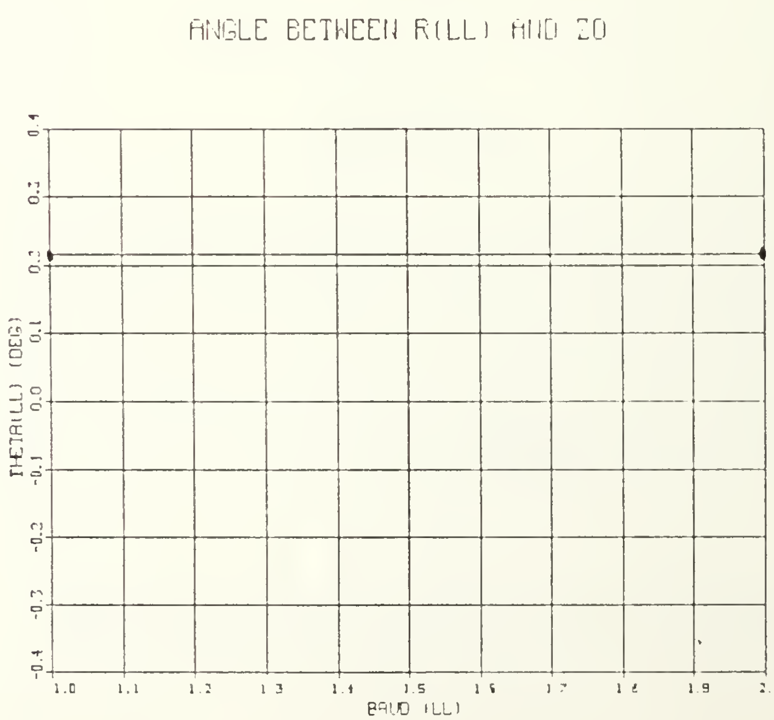
SLANT RANGE TO RECEIVER



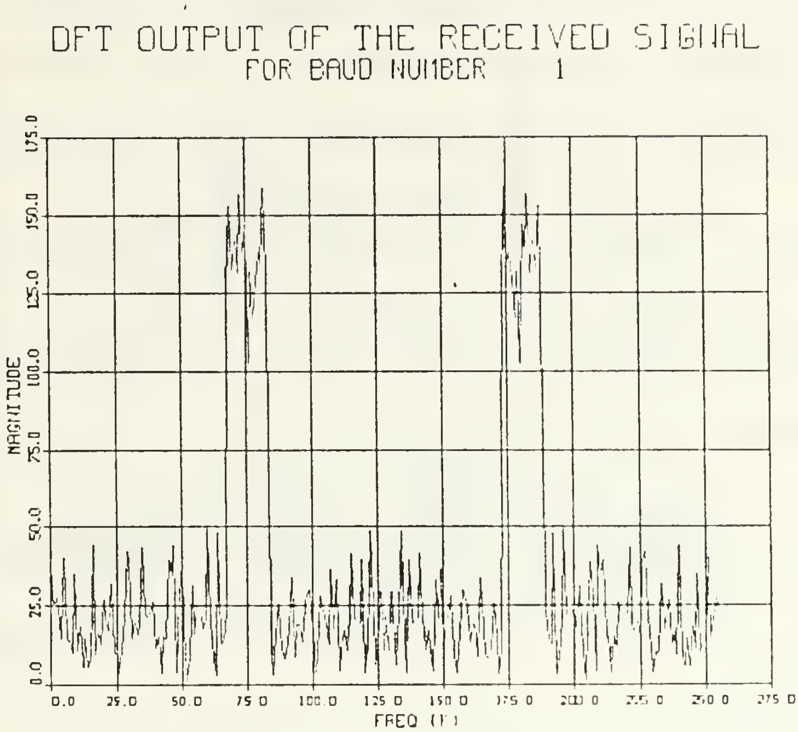
SPEED OF SOUND

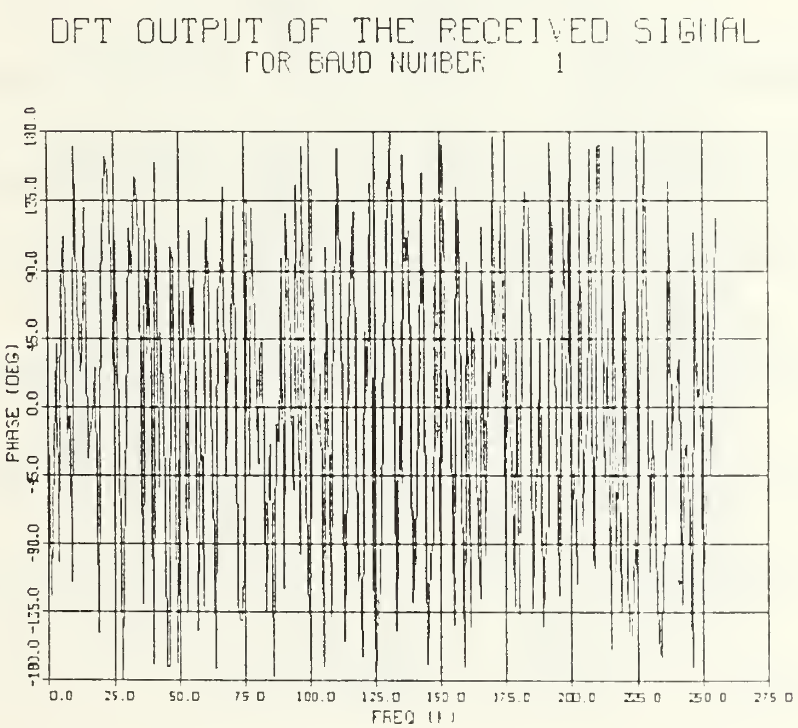



COMPRESSION FACTOR DUE TO THE MOVING TX
ALPHA(LL)
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
BAUD (LL)

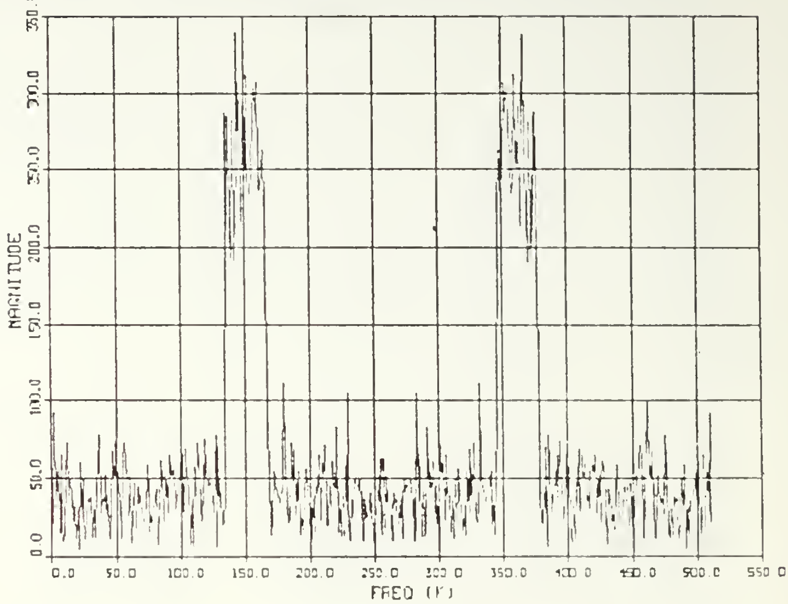

ANGLE BETWEEN R(LL) AND Z0
THETA(LL) (DEG)
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
BAUD (LL)

2. DFT Not Windowed (IWNDOW=0)

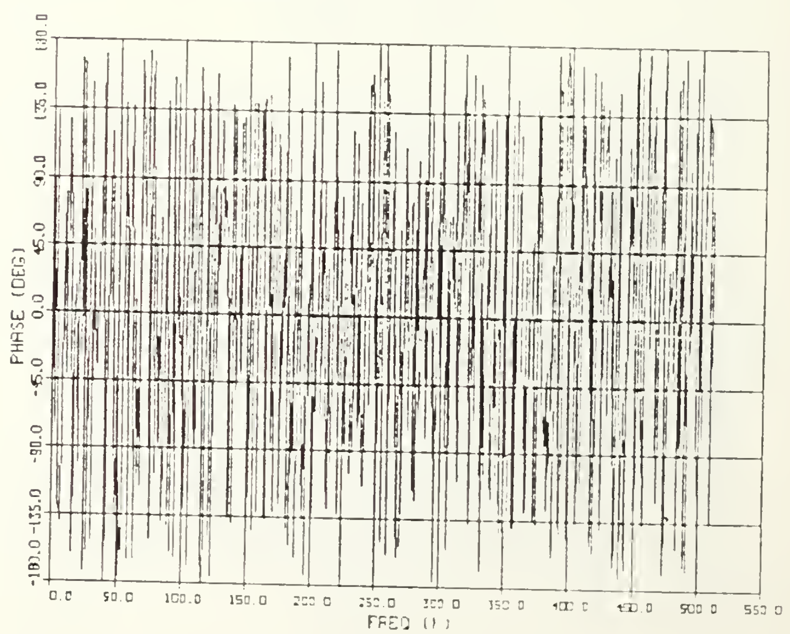




DFT OUTPUT OF THE RECEIVED SIGNAL
FOR BAUD NUMBER 2



DFT OUTPUT OF THE RECEIVED SIGNAL
FOR BAUD NUMBER 2



APPENDIX C. STATISTICS OF SNR_{OUT} VS. SNR_{IN} ANALYSIS

A. INPUT SNR = 0 dB

```
INPUT SNRNB =    1.000 =    0.000 DB

BAUD TYPE 1:  KX =  256 SAMPLE POINTS; K =  16 TONES

** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                  NUMBER OF TONES =     4
            MEAN OF DFT REAL PART =    97.73993
        VARIANCE OF DFT REAL PART =     8419.37
QUADRANT SNROUT OF DFT REAL PART =    1.1347 =    0.5486 DB

            MEAN OF DFT IMAG PART =   129.16241
        VARIANCE OF DFT IMAG PART =     6640.81
QUADRANT SNROUT OF DFT IMAG PART =    2.5122 =    4.0005 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                  NUMBER OF TONES =     2
            MEAN OF DFT REAL PART =   -85.21500
        VARIANCE OF DFT REAL PART =      429.54
QUADRANT SNROUT OF DFT REAL PART =   16.9056 =   12.2803 DB

            MEAN OF DFT IMAG PART =    82.06499
        VARIANCE OF DFT IMAG PART =     2787.80
QUADRANT SNROUT OF DFT IMAG PART =    2.4158 =    3.8305 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                  NUMBER OF TONES =     6
            MEAN OF DFT REAL PART =   -61.63330
        VARIANCE OF DFT REAL PART =    12897.87
QUADRANT SNROUT OF DFT REAL PART =    0.2945 =   -5.3089 DB

            MEAN OF DFT IMAG PART =  -157.14986
        VARIANCE OF DFT IMAG PART =     1129.39
QUADRANT SNROUT OF DFT IMAG PART =   21.8667 =   13.3978 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                  NUMBER OF TONES =     4
            MEAN OF DFT REAL PART =   135.55243
        VARIANCE OF DFT REAL PART =     7555.41
QUADRANT SNROUT OF DFT REAL PART =    2.4320 =    3.8596 DB

            MEAN OF DFT IMAG PART =  -134.99750
        VARIANCE OF DFT IMAG PART =    11628.12
QUADRANT SNROUT OF DFT IMAG PART =    1.5673 =    1.9514 DB


*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 1 ***

   TOTAL NUMBER OF POINTS, 2K =     32
                    BAUD MEAN =   113.65836
                BAUD VARIANCE =     5680.15
                  BAUD SNROUT =   2.2743 =    3.5684 DB
```

```
INPUT SNRNB =    1.000 =    0.000 DB

BAUD TYPE 2:   KX =  512 SAMPLE POINTS; K =  32 TONES

** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                    NUMBER OF TONES =     5
              MEAN OF DFT REAL PART =   137.35571
          VARIANCE OF DFT REAL PART =    14934.41
QUADRANT SNROUT OF DFT REAL PART =   1.2633 =    1.0151 DB

              MEAN OF DFT IMAG PART =   263.66382
          VARIANCE OF DFT IMAG PART =    54654.25
QUADRANT SNROUT OF DFT IMAG PART =   1.2720 =    1.0448 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                    NUMBER OF TONES =     8
              MEAN OF DFT REAL PART =  -126.14920
          VARIANCE OF DFT REAL PART =    60110.95
QUADRANT SNROUT OF DFT REAL PART =   0.2647 =   -5.7718 DB

              MEAN OF DFT IMAG PART =   137.62115
          VARIANCE OF DFT IMAG PART =    19688.26
QUADRANT SNROUT OF DFT IMAG PART =   0.9620 =   -0.1684 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                    NUMBER OF TONES =    10
              MEAN OF DFT REAL PART =  -191.87024
          VARIANCE OF DFT REAL PART =    19641.78
QUADRANT SNROUT OF DFT REAL PART =   1.8743 =    2.7283 DB

              MEAN OF DFT IMAG PART =  -288.79492
          VARIANCE OF DFT IMAG PART =    30312.55
QUADRANT SNROUT OF DFT IMAG PART =   2.7514 =    4.3956 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                    NUMBER OF TONES =     9
              MEAN OF DFT REAL PART =   154.75328
          VARIANCE OF DFT REAL PART =    40444.66
QUADRANT SNROUT OF DFT REAL PART =   0.5921 =   -2.2758 DB

              MEAN OF DFT IMAG PART =  -215.35548
          VARIANCE OF DFT IMAG PART =    21217.86
QUADRANT SNROUT OF DFT IMAG PART =   2.1858 =    3.3961 DB


*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 2 ***

   TOTAL NUMBER OF POINTS, 2K =    64
                    BAUD MEAN =   191.45129
                BAUD VARIANCE =    28251.36
                  BAUD SNROUT =   1.2974 =    1.1308 DB
```

```
INPUT SNRNB =    1.000 =    0.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES


** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                NUMBER OF TONES =    13
           MEAN OF DFT REAL PART =    295.59131
       VARIANCE OF DFT REAL PART =    171068.06
QUADRANT SNROUT OF DFT REAL PART =    0.5108 =   -2.9179 DB

           MEAN OF DFT IMAG PART =    272.87988
       VARIANCE OF DFT IMAG PART =     75231.81
QUADRANT SNROUT OF DFT IMAG PART =    0.9898 =   -0.0446 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                NUMBER OF TONES =    15
           MEAN OF DFT REAL PART =   -502.71387
       VARIANCE OF DFT REAL PART =    107979.00
QUADRANT SNROUT OF DFT REAL PART =    2.3405 =    3.6930 DB

           MEAN OF DFT IMAG PART =    393.86084
       VARIANCE OF DFT IMAG PART =     91919.19
QUADRANT SNROUT OF DFT IMAG PART =    1.6876 =    2.2728 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                NUMBER OF TONES =    20
           MEAN OF DFT REAL PART =   -365.57617
       VARIANCE OF DFT REAL PART =    158013.50
QUADRANT SNROUT OF DFT REAL PART =    0.8458 =   -0.7274 DB

           MEAN OF DFT IMAG PART =   -287.26196
       VARIANCE OF DFT IMAG PART =    110806.31
QUADRANT SNROUT OF DFT IMAG PART =    0.7447 =   -1.2801 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                NUMBER OF TONES =    16
           MEAN OF DFT REAL PART =    328.53247
       VARIANCE OF DFT REAL PART =     97164.81
QUADRANT SNROUT OF DFT REAL PART =    1.1108 =    0.4565 DB

           MEAN OF DFT IMAG PART =   -504.95386
       VARIANCE OF DFT IMAG PART =    125734.50
QUADRANT SNROUT OF DFT IMAG PART =    2.0279 =    3.0705 DB


*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 3 ***

   TOTAL NUMBER OF POINTS, 2K =    128
                    BAUD MEAN =    368.99438
                BAUD VARIANCE =    111852.19
                  BAUD SNROUT =    1.2173 =    0.8540 DB
```

```
INPUT SNRNB =   1.000 =   0.000 DB

BAUD TYPE 4:  KX = 2048 SAMPLE POINTS; K = 128 TONES

** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                 NUMBER OF TONES =   38
             MEAN OF DFT REAL PART =   765.55249
         VARIANCE OF DFT REAL PART =   480832.37
  QUADRANT SNROUT OF DFT REAL PART =   1.2189 =   0.8596 DB

             MEAN OF DFT IMAG PART =   487.95532
         VARIANCE OF DFT IMAG PART =   436912.56
  QUADRANT SNROUT OF DFT IMAG PART =   0.5450 =  -2.6363 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                 NUMBER OF TONES =   34
             MEAN OF DFT REAL PART =  -919.41406
         VARIANCE OF DFT REAL PART =   473379.37
  QUADRANT SNROUT OF DFT REAL PART =   1.7857 =   2.5181 DB

             MEAN OF DFT IMAG PART =   909.34058
         VARIANCE OF DFT IMAG PART =   403385.00
  QUADRANT SNROUT OF DFT IMAG PART =   2.0499 =   3.1173 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                 NUMBER OF TONES =   35
             MEAN OF DFT REAL PART =  -744.60986
         VARIANCE OF DFT REAL PART =   535541.62
  QUADRANT SNROUT OF DFT REAL PART =   1.0353 =   0.1506 DB

             MEAN OF DFT IMAG PART =  -645.88306
         VARIANCE OF DFT IMAG PART =   493911.50
  QUADRANT SNROUT OF DFT IMAG PART =   0.8446 =  -0.7334 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                 NUMBER OF TONES =   21
             MEAN OF DFT REAL PART =   845.74316
         VARIANCE OF DFT REAL PART =   506747.94
  QUADRANT SNROUT OF DFT REAL PART =   1.4115 =   1.4968 DB

             MEAN OF DFT IMAG PART =  -607.39453
         VARIANCE OF DFT IMAG PART =   472505.12
  QUADRANT SNROUT OF DFT IMAG PART =   0.7808 =  -1.0746 DB


*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 4 ***

   TOTAL NUMBER OF POINTS, 2K =   256
                   BAUD MEAN =   738.25732
               BAUD VARIANCE =   460690.81
                 BAUD SNROUT =   1.1831 =   0.7301 DB
```

```
INPUT SNRNB =   1.000 =   0.000 DB

BAUD TYPE 5:  KX = 4096 SAMPLE POINTS; K = 256 TONES


** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                  NUMBER OF TONES =   64
            MEAN OF DFT REAL PART =  1507.82715
        VARIANCE OF DFT REAL PART =  2880635.00
QUADRANT SNROUT OF DFT REAL PART =    0.7893 =   -1.0279 DB

            MEAN OF DFT IMAG PART =  1674.69238
        VARIANCE OF DFT IMAG PART =  2577858.00
QUADRANT SNROUT OF DFT IMAG PART =    1.0880 =    0.3661 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                  NUMBER OF TONES =   61
            MEAN OF DFT REAL PART = -1636.89526
        VARIANCE OF DFT REAL PART =  2406180.00
QUADRANT SNROUT OF DFT REAL PART =    1.1136 =    0.4671 DB

            MEAN OF DFT IMAG PART =  1345.84106
        VARIANCE OF DFT IMAG PART =  3274481.00
QUADRANT SNROUT OF DFT IMAG PART =    0.5532 =   -2.5715 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                  NUMBER OF TONES =   59
            MEAN OF DFT REAL PART = -1447.54858
        VARIANCE OF DFT REAL PART =  1710154.00
QUADRANT SNROUT OF DFT REAL PART =    1.2253 =    0.8823 DB

            MEAN OF DFT IMAG PART = -1208.50415
        VARIANCE OF DFT IMAG PART =  2686264.00
QUADRANT SNROUT OF DFT IMAG PART =    0.5437 =   -2.6465 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                  NUMBER OF TONES =   72
            MEAN OF DFT REAL PART =  1315.15088
        VARIANCE OF DFT REAL PART =  1992730.00
QUADRANT SNROUT OF DFT REAL PART =    0.8680 =   -0.6150 DB

            MEAN OF DFT IMAG PART = -1541.86792
        VARIANCE OF DFT IMAG PART =  2939624.00
QUADRANT SNROUT OF DFT IMAG PART =    0.8087 =   -0.9220 DB


*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 5 ***

   TOTAL NUMBER OF POINTS, 2K =   512
                    BAUD MEAN =  1461.01611
                BAUD VARIANCE =  2524291.00
                  BAUD SNROUT =   0.8456 =  -0.7283 DB
```

B. INPUT SNR = 5 dB

```
INPUT SNRNB =    3.162 =    5.000 DB

BAUD TYPE 1:  KX =  256 SAMPLE POINTS; K =  16 TONES

** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                   NUMBER OF TONES =     4
             MEAN OF DFT REAL PART =    94.57245
         VARIANCE OF DFT REAL PART =     2661.94
QUADRANT SNROUT OF DFT REAL PART =    3.3599 =    5.2633 DB

             MEAN OF DFT IMAG PART =   112.22491
         VARIANCE OF DFT IMAG PART =     2098.79
QUADRANT SNROUT OF DFT IMAG PART =    6.0008 =    7.7821 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                   NUMBER OF TONES =     2
             MEAN OF DFT REAL PART =   -87.53000
         VARIANCE OF DFT REAL PART =      135.80
QUADRANT SNROUT OF DFT REAL PART =  56.4194 =   17.5143 DB

             MEAN OF DFT IMAG PART =    85.78000
         VARIANCE OF DFT IMAG PART =      883.68
QUADRANT SNROUT OF DFT IMAG PART =    8.3268 =    9.2048 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                   NUMBER OF TONES =     6
             MEAN OF DFT REAL PART =   -74.27998
         VARIANCE OF DFT REAL PART =     4080.46
QUADRANT SNROUT OF DFT REAL PART =    1.3522 =    1.3103 DB

             MEAN OF DFT IMAG PART =  -127.96658
         VARIANCE OF DFT IMAG PART =      357.45
QUADRANT SNROUT OF DFT IMAG PART =  45.8118 =   16.6098 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                   NUMBER OF TONES =     4
             MEAN OF DFT REAL PART =   115.84491
         VARIANCE OF DFT REAL PART =     2387.74
QUADRANT SNROUT OF DFT REAL PART =    5.6204 =    7.4977 DB

             MEAN OF DFT IMAG PART =  -115.54242
         VARIANCE OF DFT IMAG PART =     3679.88
QUADRANT SNROUT OF DFT IMAG PART =    3.6278 =    5.5965 DB


*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 1 ***

   TOTAL NUMBER OF POINTS, 2K =     32
                    BAUD MEAN =   103.52617
                BAUD VARIANCE =     1796.58
                  BAUD SNROUT =    5.9656 =    7.7565 DB
```

```
INPUT SNRNB =    3.162 =    5.000 DB

BAUD TYPE 2:   KX =  512 SAMPLE POINTS; K =  32 TONES


** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                   NUMBER OF TONES =     5
             MEAN OF DFT REAL PART =   156.34995
         VARIANCE OF DFT REAL PART =     4717.56
QUADRANT SNROUT OF DFT REAL PART =   5.1818 =    7.1448 DB

             MEAN OF DFT IMAG PART =   227.40594
         VARIANCE OF DFT IMAG PART =    17291.69
QUADRANT SNROUT OF DFT IMAG PART =   2.9907 =    4.7577 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                   NUMBER OF TONES =     8
             MEAN OF DFT REAL PART =  -150.08240
         VARIANCE OF DFT REAL PART =    19011.11
QUADRANT SNROUT OF DFT REAL PART =   1.1848 =    0.7365 DB

             MEAN OF DFT IMAG PART =   156.51974
         VARIANCE OF DFT IMAG PART =     6230.11
QUADRANT SNROUT OF DFT IMAG PART =   3.9323 =    5.9464 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                   NUMBER OF TONES =    10
             MEAN OF DFT REAL PART =  -186.99594
         VARIANCE OF DFT REAL PART =     6212.98
QUADRANT SNROUT OF DFT REAL PART =   5.6281 =    7.5036 DB

             MEAN OF DFT IMAG PART =  -241.53493
         VARIANCE OF DFT IMAG PART =     9587.26
QUADRANT SNROUT OF DFT IMAG PART =   6.0851 =    7.8427 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                   NUMBER OF TONES =     9
             MEAN OF DFT REAL PART =   166.15880
         VARIANCE OF DFT REAL PART =    12788.79
QUADRANT SNROUT OF DFT REAL PART =   2.1588 =    3.3422 DB

             MEAN OF DFT IMAG PART =  -200.21880
         VARIANCE OF DFT IMAG PART =     6707.95
QUADRANT SNROUT OF DFT IMAG PART =   5.9761 =    7.7642 DB


*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 2 ***

   TOTAL NUMBER OF POINTS, 2K =    64
                    BAUD MEAN =   186.78583
                BAUD VARIANCE =     8934.94
                  BAUD SNROUT =   3.9048 =    5.9160 DB
```

```
INPUT SNRNB =    3.162 =    5.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES


** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                 NUMBER OF TONES =   13
            MEAN OF DFT REAL PART =   324.77417
        VARIANCE OF DFT REAL PART =    54069.19
QUADRANT SNROUT OF DFT REAL PART =   1.9508 =   2.9021 DB

            MEAN OF DFT IMAG PART =   312.15674
        VARIANCE OF DFT IMAG PART =    23785.73
QUADRANT SNROUT OF DFT IMAG PART =   4.0967 =   6.1243 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                 NUMBER OF TONES =   15
            MEAN OF DFT REAL PART =  -441.42603
        VARIANCE OF DFT REAL PART =    34121.99
QUADRANT SNROUT OF DFT REAL PART =   5.7106 =   7.5668 DB

            MEAN OF DFT IMAG PART =   380.12280
        VARIANCE OF DFT IMAG PART =    29067.91
QUADRANT SNROUT OF DFT IMAG PART =   4.9709 =   6.9643 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                 NUMBER OF TONES =   20
            MEAN OF DFT REAL PART =  -364.12720
        VARIANCE OF DFT REAL PART =    49952.47
QUADRANT SNROUT OF DFT REAL PART =   2.6543 =   4.2395 DB

            MEAN OF DFT IMAG PART =  -320.32812
        VARIANCE OF DFT IMAG PART =    35015.78
QUADRANT SNROUT OF DFT IMAG PART =   2.9304 =   4.6693 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                 NUMBER OF TONES =   16
            MEAN OF DFT REAL PART =   343.55005
        VARIANCE OF DFT REAL PART =    30738.97
QUADRANT SNROUT OF DFT REAL PART =   3.8396 =   5.8429 DB

            MEAN OF DFT IMAG PART =  -442.46045
        VARIANCE OF DFT IMAG PART =    39734.58
QUADRANT SNROUT OF DFT IMAG PART =   4.9270 =   6.9258 DB


*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 3 ***

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   366.16089
                BAUD VARIANCE =    35357.58
                  BAUD SNROUT =   3.7919 =   5.7886 DB
```

```
INPUT SNRNB =    3.162 =    5.000 DB

BAUD TYPE 4:   KX = 2048 SAMPLE POINTS; K = 128 TONES

** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                  NUMBER OF TONES =    38
            MEAN OF DFT REAL PART =    754.15430
        VARIANCE OF DFT REAL PART =    151360.81
QUADRANT SNROUT OF DFT REAL PART =    3.7576 =    5.7491 DB

            MEAN OF DFT IMAG PART =    598.70117
        VARIANCE OF DFT IMAG PART =    138265.00
QUADRANT SNROUT OF DFT IMAG PART =    2.5924 =    4.1371 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                  NUMBER OF TONES =    34
            MEAN OF DFT REAL PART =   -842.04663
        VARIANCE OF DFT REAL PART =    150349.12
QUADRANT SNROUT OF DFT REAL PART =    4.7160 =    6.7357 DB

            MEAN OF DFT IMAG PART =    834.70776
        VARIANCE OF DFT IMAG PART =    127103.50
QUADRANT SNROUT OF DFT IMAG PART =    5.4817 =    7.3891 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                  NUMBER OF TONES =    35
            MEAN OF DFT REAL PART =   -741.81006
        VARIANCE OF DFT REAL PART =    168815.31
QUADRANT SNROUT OF DFT REAL PART =    3.2597 =    5.1317 DB

            MEAN OF DFT IMAG PART =   -688.02417
        VARIANCE OF DFT IMAG PART =    155789.25
QUADRANT SNROUT OF DFT IMAG PART =    3.0386 =    4.8267 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                  NUMBER OF TONES =    21
            MEAN OF DFT REAL PART =    799.47021
        VARIANCE OF DFT REAL PART =    159680.31
QUADRANT SNROUT OF DFT REAL PART =    4.0027 =    6.0235 DB

            MEAN OF DFT IMAG PART =   -665.15771
        VARIANCE OF DFT IMAG PART =    149754.06
QUADRANT SNROUT OF DFT IMAG PART =    2.9544 =    4.7047 DB

*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 4 ***

   TOTAL NUMBER OF POINTS, 2K =    256
                   BAUD MEAN =    739.13794
               BAUD VARIANCE =    145479.56
                 BAUD SNROUT =    3.7553 =    5.7465 DB
```

```
INPUT SNRNB =    3.162 =    5.000 DB

BAUD TYPE 5:   KX = 4096 SAMPLE POINTS; K = 256 TONES

** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                     NUMBER OF TONES =    64
              MEAN OF DFT REAL PART =  1508.21289
          VARIANCE OF DFT REAL PART =   915649.00
QUADRANT SNROUT OF DFT REAL PART =    2.4843 =    3.9520 DB

              MEAN OF DFT IMAG PART =  1605.33105
          VARIANCE OF DFT IMAG PART =   823249.25
QUADRANT SNROUT OF DFT IMAG PART =    3.1304 =    4.9560 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                     NUMBER OF TONES =    61
              MEAN OF DFT REAL PART = -1585.36865
          VARIANCE OF DFT REAL PART =   762098.37
QUADRANT SNROUT OF DFT REAL PART =    3.2980 =    5.1825 DB

              MEAN OF DFT IMAG PART =  1415.77759
          VARIANCE OF DFT IMAG PART =  1035021.56
QUADRANT SNROUT OF DFT IMAG PART =    1.9366 =    2.8704 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                     NUMBER OF TONES =    59
              MEAN OF DFT REAL PART = -1473.39185
          VARIANCE OF DFT REAL PART =   538915.81
QUADRANT SNROUT OF DFT REAL PART =    4.0282 =    6.0512 DB

              MEAN OF DFT IMAG PART = -1342.45337
          VARIANCE OF DFT IMAG PART =   845222.31
QUADRANT SNROUT OF DFT IMAG PART =    2.1322 =    3.2883 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                     NUMBER OF TONES =    72
              MEAN OF DFT REAL PART =  1401.73340
          VARIANCE OF DFT REAL PART =   632763.94
QUADRANT SNROUT OF DFT REAL PART =    3.1052 =    4.9209 DB

              MEAN OF DFT IMAG PART = -1526.53638
          VARIANCE OF DFT IMAG PART =   927957.37
QUADRANT SNROUT OF DFT IMAG PART =    2.5112 =    3.9989 DB


*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 5 ***

   TOTAL NUMBER OF POINTS, 2K =   512
                    BAUD MEAN =  1483.02075
                BAUD VARIANCE =   799351.69
                  BAUD SNROUT =   2.7514 =    4.3956 DB
```

C. INPUT SNR = 10 dB

```
INPUT SNRNB =  10.000 =  10.000 DB

BAUD TYPE 1:  KX =  256 SAMPLE POINTS; K =  16 TONES

** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                 NUMBER OF TONES =    4
           MEAN OF DFT REAL PART =    92.78491
       VARIANCE OF DFT REAL PART =      840.84
QUADRANT SNROUT OF DFT REAL PART =  10.2386 =  10.1024 DB

           MEAN OF DFT IMAG PART =   102.71246
       VARIANCE OF DFT IMAG PART =      663.56
QUADRANT SNROUT OF DFT IMAG PART =  15.8989 =  12.0137 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                 NUMBER OF TONES =    2
           MEAN OF DFT REAL PART =   -88.83499
       VARIANCE OF DFT REAL PART =       42.97
QUADRANT SNROUT OF DFT REAL PART = 183.6700 =  22.6404 DB

           MEAN OF DFT IMAG PART =    87.84000
       VARIANCE OF DFT IMAG PART =      278.95
QUADRANT SNROUT OF DFT IMAG PART =  27.6602 =  14.4185 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                 NUMBER OF TONES =    6
           MEAN OF DFT REAL PART =   -81.36990
       VARIANCE OF DFT REAL PART =     1289.56
QUADRANT SNROUT OF DFT REAL PART =   5.1344 =   7.1049 DB

           MEAN OF DFT IMAG PART =  -111.58658
       VARIANCE OF DFT IMAG PART =      113.19
QUADRANT SNROUT OF DFT IMAG PART = 110.0076 =  20.4142 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                 NUMBER OF TONES =    4
           MEAN OF DFT REAL PART =   104.76740
       VARIANCE OF DFT REAL PART =      756.27
QUADRANT SNROUT OF DFT REAL PART =  14.5137 =  11.6178 DB

           MEAN OF DFT IMAG PART =  -104.59491
       VARIANCE OF DFT IMAG PART =     1164.08
QUADRANT SNROUT OF DFT IMAG PART =   9.3981 =   9.7304 DB

*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 1  ***

   TOTAL NUMBER OF POINTS, 2K =     32
                   BAUD MEAN =     97.82896
               BAUD VARIANCE =       568.06
                 BAUD SNROUT =  16.8477 =  12.2654 DB
```

```
INPUT SNRNB =  10.000 =  10.000 DB

BAUD TYPE 2:  KX =  512 SAMPLE POINTS; K =  32 TONES


** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                  NUMBER OF TONES =     5
            MEAN OF DFT REAL PART =   167.03993
        VARIANCE OF DFT REAL PART =     1490.65
QUADRANT SNROUT OF DFT REAL PART =  18.7182 =  12.7226 DB

            MEAN OF DFT IMAG PART =   207.00189
        VARIANCE OF DFT IMAG PART =     5471.27
QUADRANT SNROUT OF DFT IMAG PART =   7.8318 =   8.9386 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                  NUMBER OF TONES =     8
            MEAN OF DFT REAL PART =  -163.52493
        VARIANCE OF DFT REAL PART =     6010.42
QUADRANT SNROUT OF DFT REAL PART =   4.4490 =   6.4826 DB

            MEAN OF DFT IMAG PART =   167.12369
        VARIANCE OF DFT IMAG PART =     1969.51
QUADRANT SNROUT OF DFT IMAG PART =  14.1813 =  11.5172 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                  NUMBER OF TONES =    10
            MEAN OF DFT REAL PART =  -184.25990
        VARIANCE OF DFT REAL PART =     1965.78
QUADRANT SNROUT OF DFT REAL PART =  17.2714 =  12.3733 DB

            MEAN OF DFT IMAG PART =  -214.98996
        VARIANCE OF DFT IMAG PART =     3034.56
QUADRANT SNROUT OF DFT IMAG PART =  15.2314 =  11.8274 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                  NUMBER OF TONES =     9
            MEAN OF DFT REAL PART =   172.58655
        VARIANCE OF DFT REAL PART =     4046.22
QUADRANT SNROUT OF DFT REAL PART =   7.3615 =   8.6696 DB

            MEAN OF DFT IMAG PART =  -191.69989
        VARIANCE OF DFT IMAG PART =     2121.56
QUADRANT SNROUT OF DFT IMAG PART =  17.3216 =  12.3859 DB


*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 2  ***

   TOTAL NUMBER OF POINTS, 2K =    64
                    BAUD MEAN =   184.16351
                BAUD VARIANCE =     2826.23
                  BAUD SNROUT = 12.0005 =  10.7920 DB
```

```
INPUT SNRNB =  10.000 =  10.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES

** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                  NUMBER OF TONES =   13
            MEAN OF DFT REAL PART =   341.20361
        VARIANCE OF DFT REAL PART =    17078.35
QUADRANT SNROUT OF DFT REAL PART =   6.8168 =   8.3358 DB

            MEAN OF DFT IMAG PART =   334.22290
        VARIANCE OF DFT IMAG PART =     7515.77
QUADRANT SNROUT OF DFT IMAG PART =  14.8627 =  11.7210 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                  NUMBER OF TONES =   15
            MEAN OF DFT REAL PART =  -406.96606
        VARIANCE OF DFT REAL PART =    10785.23
QUADRANT SNROUT OF DFT REAL PART =  15.3563 =  11.8629 DB

            MEAN OF DFT IMAG PART =   372.41919
        VARIANCE OF DFT IMAG PART =     9200.02
QUADRANT SNROUT OF DFT IMAG PART =  15.0756 =  11.7828 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                  NUMBER OF TONES =   20
            MEAN OF DFT REAL PART =  -363.32935
        VARIANCE OF DFT REAL PART =    15794.66
QUADRANT SNROUT OF DFT REAL PART =   8.3578 =   9.2209 DB

            MEAN OF DFT IMAG PART =  -338.93921
        VARIANCE OF DFT IMAG PART =    11063.66
QUADRANT SNROUT OF DFT IMAG PART =  10.3835 =  10.1634 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                  NUMBER OF TONES =   16
            MEAN OF DFT REAL PART =   351.99341
        VARIANCE OF DFT REAL PART =     9729.22
QUADRANT SNROUT OF DFT REAL PART =  12.7348 =  11.0499 DB

            MEAN OF DFT IMAG PART =  -407.30591
        VARIANCE OF DFT IMAG PART =    12552.48
QUADRANT SNROUT OF DFT IMAG PART =  13.2164 =  11.2111 DB


*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 3  ***

   TOTAL NUMBER OF POINTS, 2K =   128
                   BAUD MEAN =   364.57397
               BAUD VARIANCE =    11176.81
                 BAUD SNROUT =  11.8920 =  10.7525 DB
```

```
INPUT SNRNB =  10.000 =  10.000 DB

BAUD TYPE 4:  KX = 2048 SAMPLE POINTS; K = 128 TONES


** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                 NUMBER OF TONES =   38
         MEAN OF DFT REAL PART =   747.69604
     VARIANCE OF DFT REAL PART =    47469.11
QUADRANT SNROUT OF DFT REAL PART =  11.7771 =  10.7104 DB

         MEAN OF DFT IMAG PART =   660.96704
     VARIANCE OF DFT IMAG PART =    43777.00
QUADRANT SNROUT OF DFT IMAG PART =   9.9796 =   9.9911 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                 NUMBER OF TONES =   34
         MEAN OF DFT REAL PART =  -798.57202
     VARIANCE OF DFT REAL PART =    47932.87
QUADRANT SNROUT OF DFT REAL PART =  13.3044 =  11.2399 DB

         MEAN OF DFT IMAG PART =   792.75439
     VARIANCE OF DFT IMAG PART =    39958.12
QUADRANT SNROUT OF DFT IMAG PART =  15.7280 =  11.9667 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                 NUMBER OF TONES =   35
         MEAN OF DFT REAL PART =  -740.16992
     VARIANCE OF DFT REAL PART =    53078.29
QUADRANT SNROUT OF DFT REAL PART =  10.3216 =  10.1375 DB

         MEAN OF DFT IMAG PART =  -711.70435
     VARIANCE OF DFT IMAG PART =    49063.26
QUADRANT SNROUT OF DFT IMAG PART =  10.3239 =  10.1384 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                 NUMBER OF TONES =   21
         MEAN OF DFT REAL PART =   773.37500
     VARIANCE OF DFT REAL PART =    50136.43
QUADRANT SNROUT OF DFT REAL PART =  11.9296 =  10.7663 DB

         MEAN OF DFT IMAG PART =  -697.57031
     VARIANCE OF DFT IMAG PART =    47513.27
QUADRANT SNROUT OF DFT IMAG PART =  10.2414 =  10.1036 DB


*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 4  ***

   TOTAL NUMBER OF POINTS, 2K =   256
                    BAUD MEAN =   739.60791
                BAUD VARIANCE =    45891.41
                  BAUD SNROUT =  11.9199 =  10.7627 DB
```

```
INPUT SNRNB =  10.000 =  10.000 DB

BAUD TYPE 5:  KX = 4096 SAMPLE POINTS; K = 256 TONES

** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                 NUMBER OF TONES =    64
           MEAN OF DFT REAL PART =  1508.31250
       VARIANCE OF DFT REAL PART =   292452.31
QUADRANT SNROUT OF DFT REAL PART =   7.7791 =   8.9093 DB

           MEAN OF DFT IMAG PART =  1566.18359
       VARIANCE OF DFT IMAG PART =   265130.50
QUADRANT SNROUT OF DFT IMAG PART =   9.2518 =   9.6623 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                 NUMBER OF TONES =    61
           MEAN OF DFT REAL PART = -1556.26514
       VARIANCE OF DFT REAL PART =   242012.25
QUADRANT SNROUT OF DFT REAL PART =  10.0076 =  10.0033 DB

           MEAN OF DFT IMAG PART =  1455.11865
       VARIANCE OF DFT IMAG PART =   327317.06
QUADRANT SNROUT OF DFT IMAG PART =   6.4689 =   8.1083 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                 NUMBER OF TONES =    59
           MEAN OF DFT REAL PART = -1487.87915
       VARIANCE OF DFT REAL PART =   169614.31
QUADRANT SNROUT OF DFT REAL PART =  13.0519 =  11.1567 DB

           MEAN OF DFT IMAG PART = -1417.67261
       VARIANCE OF DFT IMAG PART =   265248.00
QUADRANT SNROUT OF DFT IMAG PART =   7.5770 =   8.7950 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                 NUMBER OF TONES =    72
           MEAN OF DFT REAL PART =  1450.37061
       VARIANCE OF DFT REAL PART =   202104.12
QUADRANT SNROUT OF DFT REAL PART =  10.4084 =  10.1738 DB

           MEAN OF DFT IMAG PART = -1517.82886
       VARIANCE OF DFT IMAG PART =   292801.12
QUADRANT SNROUT OF DFT IMAG PART =   7.8682 =   8.9587 DB


*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 5  ***

   TOTAL NUMBER OF POINTS, 2K =    512
                   BAUD MEAN =  1495.31201
               BAUD VARIANCE =   253713.62
                 BAUD SNROUT =   8.8129 =   9.4512 DB
```

D. INPUT SNR = 15 dB

```
INPUT SNRNB =  31.623 =  15.000 DB

BAUD TYPE 1:  KX =  256 SAMPLE POINTS; K =  16 TONES

** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                 NUMBER OF TONES =    4
               MEAN OF DFT REAL PART =    91.78998
   VARIANCE OF DFT REAL PART =       265.70
QUADRANT SNROUT OF DFT REAL PART =  31.7097 =  15.0119 DB

               MEAN OF DFT IMAG. PART =    97.37494
   VARIANCE OF DFT IMAG PART =       209.96
QUADRANT SNROUT OF DFT IMAG PART =  45.1599 =  16.5475 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                 NUMBER OF TONES =    2
               MEAN OF DFT REAL PART =   -89.56999
   VARIANCE OF DFT REAL PART =        13.62
QUADRANT SNROUT OF DFT REAL PART = 588.8657 =  27.7002 DB

               MEAN OF DFT IMAG PART =    89.00999
   VARIANCE OF DFT IMAG PART =        88.18
QUADRANT SNROUT OF DFT IMAG PART =  89.8486 =  19.5351 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                 NUMBER OF TONES =    6
               MEAN OF DFT REAL PART =   -85.36328
   VARIANCE OF DFT REAL PART =       407.69
QUADRANT SNROUT OF DFT REAL PART =  17.8737 =  12.5221 DB

               MEAN OF DFT IMAG PART =  -102.36160
   VARIANCE OF DFT IMAG PART =        35.63
QUADRANT SNROUT OF DFT IMAG PART = 294.1055 =  24.6850 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                 NUMBER OF TONES =    4
               MEAN OF DFT REAL PART =    98.51746
   VARIANCE OF DFT REAL PART =       238.91
QUADRANT SNROUT OF DFT REAL PART =  40.6241 =  16.0878 DB

               MEAN OF DFT IMAG PART =   -98.39490
   VARIANCE OF DFT IMAG PART =       366.81
QUADRANT SNROUT OF DFT IMAG PART =  26.3941 =  14.2151 DB

*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 1 ***

   TOTAL NUMBER OF POINTS, 2K =    32
                    BAUD MEAN =   94.61931
                BAUD VARIANCE =     179.44
                  BAUD SNROUT =  49.8941 =  16.9805 DB
```

```
INPUT SNRNB =  31.623 =  15.000 DB

BAUD TYPE 2:  KX =  512 SAMPLE POINTS; K =  32 TONES

** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                   NUMBER OF TONES =    5
             MEAN OF DFT REAL PART =   173.05991
         VARIANCE OF DFT REAL PART =      469.50
  QUADRANT SNROUT OF DFT REAL PART =  63.7903 =  18.0475 DB

             MEAN OF DFT IMAG PART =   195.51991
         VARIANCE OF DFT IMAG PART =     1735.51
  QUADRANT SNROUT OF DFT IMAG PART =  22.0270 =  13.4295 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                   NUMBER OF TONES =    8
             MEAN OF DFT REAL PART =  -171.09995
         VARIANCE OF DFT REAL PART =     1899.12
  QUADRANT SNROUT OF DFT REAL PART =  15.4151 =  11.8795 DB

             MEAN OF DFT IMAG PART =   173.09988
         VARIANCE OF DFT IMAG PART =      623.56
  QUADRANT SNROUT OF DFT IMAG PART =  48.0524 =  16.8171 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                   NUMBER OF TONES =   10
             MEAN OF DFT REAL PART =  -182.69992
         VARIANCE OF DFT REAL PART =      622.43
  QUADRANT SNROUT OF DFT REAL PART =  53.6277 =  17.2939 DB

             MEAN OF DFT IMAG PART =  -200.01991
         VARIANCE OF DFT IMAG PART =      961.04
  QUADRANT SNROUT OF DFT IMAG PART =  41.6297 =  16.1940 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                   NUMBER OF TONES =    9
             MEAN OF DFT REAL PART =   176.17767
         VARIANCE OF DFT REAL PART =     1279.21
  QUADRANT SNROUT OF DFT REAL PART =  24.2639 =  13.8496 DB

             MEAN OF DFT IMAG PART =  -186.88879
         VARIANCE OF DFT IMAG PART =      670.12
  QUADRANT SNROUT OF DFT IMAG PART =  52.1213 =  17.1702 DB


*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 2 ***

   TOTAL NUMBER OF POINTS, 2K =    64
                    BAUD MEAN =   182.67627
                BAUD VARIANCE =      894.04
                  BAUD SNROUT =  37.3256 =  15.7201 DB
```

```
INPUT SNRNB =  31.623 =  15.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES

** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                 NUMBER OF TONES =   13
            MEAN OF DFT REAL PART =   350.43823
        VARIANCE OF DFT REAL PART =     5392.23
QUADRANT SNROUT OF DFT REAL PART =  22.7748 =  13.5745 DB

            MEAN OF DFT IMAG PART =   346.65332
        VARIANCE OF DFT IMAG PART =     2375.41
QUADRANT SNROUT OF DFT IMAG PART =  50.5885 =  17.0405 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                 NUMBER OF TONES =   15
            MEAN OF DFT REAL PART =  -387.58618
        VARIANCE OF DFT REAL PART =     3403.85
QUADRANT SNROUT OF DFT REAL PART =  44.1332 =  16.4476 DB

            MEAN OF DFT IMAG PART =   368.07251
        VARIANCE OF DFT IMAG PART =     2911.24
QUADRANT SNROUT OF DFT IMAG PART =  46.5359 =  16.6779 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                 NUMBER OF TONES =   20
            MEAN OF DFT REAL PART =  -362.88428
        VARIANCE OF DFT REAL PART =     4993.27
QUADRANT SNROUT OF DFT REAL PART =  26.3725 =  14.2115 DB

            MEAN OF DFT IMAG PART =  -349.39429
        VARIANCE OF DFT IMAG PART =     3493.32
QUADRANT SNROUT OF DFT IMAG PART =  34.9457 =  15.4339 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                 NUMBER OF TONES =   16
            MEAN OF DFT REAL PART =   356.73682
        VARIANCE OF DFT REAL PART =     3080.93
QUADRANT SNROUT OF DFT REAL PART =  41.3060 =  16.1601 DB

            MEAN OF DFT IMAG PART =  -387.54321
        VARIANCE OF DFT IMAG PART =     3962.38
QUADRANT SNROUT OF DFT IMAG PART =  37.9039 =  15.7868 DB


*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 3 ***

   TOTAL NUMBER OF POINTS, 2K =   128
                   BAUD MEAN =   363.68042
               BAUD VARIANCE =     3531.64
                 BAUD SNROUT =  37.4510 =  15.7346 DB
```

```
INPUT SNRNB =  31.623 =  15.000 DB

BAUD TYPE 4:  KX = 2048 SAMPLE POINTS; K = 128 TONES

** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                     NUMBER OF TONES =   38
              MEAN OF DFT REAL PART =   744.14038
          VARIANCE OF DFT REAL PART =    14843.46
QUADRANT SNROUT OF DFT REAL PART =  37.3056 =  15.7177 DB

              MEAN OF DFT IMAG PART =   696.01440
          VARIANCE OF DFT IMAG PART =    13916.01
QUADRANT SNROUT OF DFT IMAG PART =  34.8114 =  15.4172 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                     NUMBER OF TONES =   34
              MEAN OF DFT REAL PART =  -774.12231
          VARIANCE OF DFT REAL PART =    15403.46
QUADRANT SNROUT OF DFT REAL PART =  38.9046 =  15.9000 DB

              MEAN OF DFT IMAG PART =   769.15747
          VARIANCE OF DFT IMAG PART =    12525.41
QUADRANT SNROUT OF DFT IMAG PART =  47.2322 =  16.7424 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                     NUMBER OF TONES =   35
              MEAN OF DFT REAL PART =  -739.27295
          VARIANCE OF DFT REAL PART =    16651.30
QUADRANT SNROUT OF DFT REAL PART =  32.8217 =  15.1616 DB

              MEAN OF DFT IMAG PART =  -725.06152
          VARIANCE OF DFT IMAG PART =    15437.08
QUADRANT SNROUT OF DFT IMAG PART =  34.0553 =  15.3218 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                     NUMBER OF TONES =   21
              MEAN OF DFT REAL PART =   758.77905
          VARIANCE OF DFT REAL PART =    15687.69
QUADRANT SNROUT OF DFT REAL PART =  36.7005 =  15.6467 DB

              MEAN OF DFT IMAG PART =  -715.81812
          VARIANCE OF DFT IMAG PART =    15135.91
QUADRANT SNROUT OF DFT IMAG PART =  33.8530 =  15.2960 DB


*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 4 ***

   TOTAL NUMBER OF POINTS, 2K =   256
                    BAUD MEAN =   739.90381
                BAUD VARIANCE =    14483.24
                  BAUD SNROUT =  37.7994 =  15.7748 DB
```

```
INPUT SNRNB =  31.623 =  15.000 DB

BAUD TYPE 5:  KX = 4096 SAMPLE POINTS; K = 256 TONES

** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                 NUMBER OF TONES =    64
            MEAN OF DFT REAL PART =  1508.39551
        VARIANCE OF DFT REAL PART =    94514.62
QUADRANT SNROUT OF DFT REAL PART =  24.0731 =  13.8153 DB

            MEAN OF DFT IMAG PART =  1544.17187
        VARIANCE OF DFT IMAG PART =    87073.12
QUADRANT SNROUT OF DFT IMAG PART =  27.3846 =  14.3751 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                 NUMBER OF TONES =    61
            MEAN OF DFT REAL PART = -1539.88403
        VARIANCE OF DFT REAL PART =    77501.44
QUADRANT SNROUT OF DFT REAL PART =  30.5961 =  14.8567 DB

            MEAN OF DFT IMAG PART =  1477.20898
        VARIANCE OF DFT IMAG PART =   103902.56
QUADRANT SNROUT OF DFT IMAG PART =  21.0018 =  13.2226 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                 NUMBER OF TONES =    59
            MEAN OF DFT REAL PART = -1496.03369
        VARIANCE OF DFT REAL PART =    53483.48
QUADRANT SNROUT OF DFT REAL PART =  41.8469 =  16.2166 DB

            MEAN OF DFT IMAG PART = -1459.93311
        VARIANCE OF DFT IMAG PART =    83136.06
QUADRANT SNROUT OF DFT IMAG PART =  25.6375 =  14.0888 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                 NUMBER OF TONES =    72
            MEAN OF DFT REAL PART =  1477.83325
        VARIANCE OF DFT REAL PART =    65498.62
QUADRANT SNROUT OF DFT REAL PART =  33.3441 =  15.2302 DB

            MEAN OF DFT IMAG PART = -1512.91821
        VARIANCE OF DFT IMAG PART =    92605.37
QUADRANT SNROUT OF DFT IMAG PART =  24.7169 =  13.9299 DB

*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 5 ***

   TOTAL NUMBER OF POINTS, 2K =   512
                    BAUD MEAN =  1502.23193
                BAUD VARIANCE =    81161.50
                  BAUD SNROUT =  27.8051 =  14.4412 DB
```

E. INPUT SNR = 20 dB

```
INPUT SNRNB = 100.000 =   20.000 DB

BAUD TYPE 1:   KX =   256 SAMPLE POINTS; K =   16 TONES

** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                 NUMBER OF TONES =     4
           MEAN OF DFT REAL PART =     91.23743
       VARIANCE OF DFT REAL PART =        84.15
QUADRANT SNROUT OF DFT REAL PART =   98.9206 =   19.9529 DB

           MEAN OF DFT IMAG PART =     94.37244
       VARIANCE OF DFT IMAG PART =        66.41
QUADRANT SNROUT OF DFT IMAG PART = 134.1027 =   21.2744 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                 NUMBER OF TONES =     2
           MEAN OF DFT REAL PART =    -89.98000
       VARIANCE OF DFT REAL PART =         4.32
QUADRANT SNROUT OF DFT REAL PART = ****** =   32.7263 DB

           MEAN OF DFT IMAG PART =     89.66499
       VARIANCE OF DFT IMAG PART =        27.90
QUADRANT SNROUT OF DFT IMAG PART = 288.1604 =   24.5963 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                 NUMBER OF TONES =     6
           MEAN OF DFT REAL PART =    -87.61157
       VARIANCE OF DFT REAL PART =       129.06
QUADRANT SNROUT OF DFT REAL PART =   59.4730 =   17.7432 DB

           MEAN OF DFT IMAG PART =    -97.17159
       VARIANCE OF DFT IMAG PART =        11.23
QUADRANT SNROUT OF DFT IMAG PART = 840.5669 =   29.2457 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                 NUMBER OF TONES =     4
           MEAN OF DFT REAL PART =     95.00745
       VARIANCE OF DFT REAL PART =        75.29
QUADRANT SNROUT OF DFT REAL PART = 119.8836 =   20.7876 DB

           MEAN OF DFT IMAG PART =    -94.95740
       VARIANCE OF DFT IMAG PART =       116.38
QUADRANT SNROUT OF DFT IMAG PART =   77.4774 =   18.8917 DB


*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 1 ***

   TOTAL NUMBER OF POINTS, 2K =     32
                   BAUD MEAN =     92.82147
               BAUD VARIANCE =        56.79
                 BAUD SNROUT = 151.7199 =   21.8104 DB
```

```
INPUT SNRNB = 100.000 =  20.000 DB

BAUD TYPE 2:  KX =  512 SAMPLE POINTS; K =  32 TONES


** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                NUMBER OF TONES =    5
           MEAN OF DFT REAL PART =   176.45985
       VARIANCE OF DFT REAL PART =      147.68
QUADRANT SNROUT OF DFT REAL PART = 210.8442 =  23.2396 DB

           MEAN OF DFT IMAG PART =   189.09990
       VARIANCE OF DFT IMAG PART =      549.10
QUADRANT SNROUT OF DFT IMAG PART =  65.1219 =  18.1373 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                NUMBER OF TONES =    8
           MEAN OF DFT REAL PART =  -175.34995
       VARIANCE OF DFT REAL PART =      599.80
QUADRANT SNROUT OF DFT REAL PART =  51.2631 =  17.0980 DB

           MEAN OF DFT IMAG PART =   176.44992
       VARIANCE OF DFT IMAG PART =      197.26
QUADRANT SNROUT OF DFT IMAG PART = 157.8330 =  21.9820 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                NUMBER OF TONES =   10
           MEAN OF DFT REAL PART =  -181.83990
       VARIANCE OF DFT REAL PART =      197.03
QUADRANT SNROUT OF DFT REAL PART = 167.8235 =  22.2485 DB

           MEAN OF DFT IMAG PART =  -191.60988
       VARIANCE OF DFT IMAG PART =      304.44
QUADRANT SNROUT OF DFT IMAG PART = 120.5977 =  20.8134 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                NUMBER OF TONES =    9
           MEAN OF DFT REAL PART =   178.21101
       VARIANCE OF DFT REAL PART =      405.12
QUADRANT SNROUT OF DFT REAL PART =  78.3938 =  18.9428 DB

           MEAN OF DFT IMAG PART =  -184.21101
       VARIANCE OF DFT IMAG PART =      211.55
QUADRANT SNROUT OF DFT IMAG PART = 160.4063 =  22.0522 DB


*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 2 ***

   TOTAL NUMBER OF POINTS, 2K =    64
                    BAUD MEAN =   181.85138
                BAUD VARIANCE =      282.75
                  BAUD SNROUT = 116.9591 =  20.6803 DB
```

```
INPUT SNRNB = 100.000 =  20.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES


** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                 NUMBER OF TONES =   13
           MEAN OF DFT REAL PART =   355.62256
       VARIANCE OF DFT REAL PART =      1701.75
QUADRANT SNROUT OF DFT REAL PART =  74.3160 =  18.7108 DB

           MEAN OF DFT IMAG PART =   353.64551
       VARIANCE OF DFT IMAG PART =       749.14
QUADRANT SNROUT OF DFT IMAG PART = 166.9445 =  22.2257 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                 NUMBER OF TONES =   15
           MEAN OF DFT REAL PART =  -376.68604
       VARIANCE OF DFT REAL PART =      1074.68
QUADRANT SNROUT OF DFT REAL PART = 132.0319 =  21.2068 DB

           MEAN OF DFT IMAG PART =   365.62622
       VARIANCE OF DFT IMAG PART =       922.01
QUADRANT SNROUT OF DFT IMAG PART = 144.9895 =  21.6134 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                 NUMBER OF TONES =   20
           MEAN OF DFT REAL PART =  -362.62378
       VARIANCE OF DFT REAL PART =      1577.91
QUADRANT SNROUT OF DFT REAL PART =  83.3354 =  19.2083 DB

           MEAN OF DFT IMAG PART =  -355.27930
       VARIANCE OF DFT IMAG PART =      1101.76
QUADRANT SNROUT OF DFT IMAG PART = 114.5647 =  20.5905 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                 NUMBER OF TONES =   16
           MEAN OF DFT REAL PART =   359.39941
       VARIANCE OF DFT REAL PART =       977.57
QUADRANT SNROUT OF DFT REAL PART = 132.1315 =  21.2101 DB

           MEAN OF DFT IMAG PART =  -376.43091
       VARIANCE OF DFT IMAG PART =      1248.45
QUADRANT SNROUT OF DFT IMAG PART = 113.5008 =  20.5500 DB


*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 3 ***

   TOTAL NUMBER OF POINTS, 2K =   128
                   BAUD MEAN =   363.17578
               BAUD VARIANCE =      1115.50
                 BAUD SNROUT = 118.2399 =  20.7276 DB
```

```
INPUT SNRNB = 100.000 =  20.000 DB

BAUD TYPE 4:   KX = 2048 SAMPLE POINTS; K = 128 TONES


** GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                 NUMBER OF TONES =    38
           MEAN OF DFT REAL PART =   742.11963
       VARIANCE OF DFT REAL PART =     4625.64
QUADRANT SNROUT OF DFT REAL PART = 119.0627 =  20.7578 DB

           MEAN OF DFT IMAG PART =   715.70630
       VARIANCE OF DFT IMAG PART =     4457.19
QUADRANT SNROUT OF DFT IMAG PART = 114.9235 =  20.6041 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                 NUMBER OF TONES =    34
           MEAN OF DFT REAL PART =  -760.36914
       VARIANCE OF DFT REAL PART =     5032.17
QUADRANT SNROUT OF DFT REAL PART = 114.8930 =  20.6029 DB

           MEAN OF DFT IMAG PART =   755.90723
       VARIANCE OF DFT IMAG PART =     3920.06
QUADRANT SNROUT OF DFT IMAG PART = 145.7620 =  21.6364 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                 NUMBER OF TONES =    35
           MEAN OF DFT REAL PART =  -738.78418
       VARIANCE OF DFT REAL PART =     5230.00
QUADRANT SNROUT OF DFT REAL PART = 104.3598 =  20.1853 DB

           MEAN OF DFT IMAG PART =  -732.57861
       VARIANCE OF DFT IMAG PART =     4854.96
QUADRANT SNROUT OF DFT IMAG PART = 110.5407 =  20.4352 DB


** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                 NUMBER OF TONES =    21
           MEAN OF DFT REAL PART =   750.57007
       VARIANCE OF DFT REAL PART =     4882.30
QUADRANT SNROUT OF DFT REAL PART = 115.3872 =  20.6216 DB

           MEAN OF DFT IMAG PART =  -726.06567
       VARIANCE OF DFT IMAG PART =     4864.54
QUADRANT SNROUT OF DFT IMAG PART = 108.3701 =  20.3491 DB


*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 4 ***

   TOTAL NUMBER OF POINTS, 2K =   256
                    BAUD MEAN =   740.06909
                BAUD VARIANCE =     4585.54
                  BAUD SNROUT = 119.4413 =  20.7715 DB
```

```
INPUT SNRNB = 100.000 =  20.000 DB

BAUD TYPE 5:  KX = 4096 SAMPLE POINTS; K = 256 TONES

**  GIVEN THE TRANSMITTED PHASE IS IN THE 1ST QUADRANT **

                   NUMBER OF TONES =   64
             MEAN OF DFT REAL PART =  1508.39062
         VARIANCE OF DFT REAL PART =    31407.17
 QUADRANT SNROUT OF DFT REAL PART =  72.4434 =  18.6000 DB

             MEAN OF DFT IMAG PART =  1531.78125
         VARIANCE OF DFT IMAG PART =    29779.73
 QUADRANT SNROUT OF DFT IMAG PART =  78.7903 =  18.9647 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 2ND QUADRANT **

                   NUMBER OF TONES =   61
             MEAN OF DFT REAL PART = -1530.73755
         VARIANCE OF DFT REAL PART =    25465.21
 QUADRANT SNROUT OF DFT REAL PART =  92.0140 =  19.6385 DB

             MEAN OF DFT IMAG PART =  1489.81445
         VARIANCE OF DFT IMAG PART =    33534.58
 QUADRANT SNROUT OF DFT IMAG PART =  66.1868 =  18.2077 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 3RD QUADRANT **

                   NUMBER OF TONES =   59
             MEAN OF DFT REAL PART = -1500.62695
         VARIANCE OF DFT REAL PART =    17125.93
 QUADRANT SNROUT OF DFT REAL PART = 131.4895 =  21.1889 DB

             MEAN OF DFT IMAG PART = -1483.72876
         VARIANCE OF DFT IMAG PART =    26270.10
 QUADRANT SNROUT OF DFT IMAG PART =  83.8006 =  19.2325 DB

** GIVEN THE TRANSMITTED PHASE IS IN THE 4TH QUADRANT **

                   NUMBER OF TONES =   72
             MEAN OF DFT REAL PART =  1493.18042
         VARIANCE OF DFT REAL PART =    22084.69
 QUADRANT SNROUT OF DFT REAL PART = 100.9562 =  20.0413 DB

             MEAN OF DFT IMAG PART = -1510.18042
         VARIANCE OF DFT IMAG PART =    29661.86
 QUADRANT SNROUT OF DFT IMAG PART =  76.8881 =  18.8586 DB


*** OVERALL (REAL + IMAG) STATISTICS FOR BAUD TYPE 5 ***

    TOTAL NUMBER OF POINTS, 2K =   512
                    BAUD MEAN =  1506.13916
                BAUD VARIANCE =    26586.55
                  BAUD SNROUT =  85.3234 =  19.3107 DB
```

APPENDIX D. STATISTICS OF SNR_{OUT} VS. DOPPLER ANALYSIS

A. INPUT SNR = 15 dB

```
SNROUT VS. DOPPLER TEST -- EPSILON =  0.00

INPUT SNRNB =   31.623 =   15.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES


** OVERALL (REAL + IMAG) STATISTICS FOR THE 1ST BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   358.19678
                BAUD VARIANCE =     3614.89
                  BAUD SNROUT =   35.4935 =    15.5015 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 2ND BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   359.38672
                BAUD VARIANCE =     4296.25
                  BAUD SNROUT =   30.0631 =    14.7803 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 3RD BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   353.96387
                BAUD VARIANCE =     3632.05
                  BAUD SNROUT =   34.4958 =    15.3777 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 4TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   360.04858
                BAUD VARIANCE =     3868.04
                  BAUD SNROUT =   33.5144 =    15.2523 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 5TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   344.44604
                BAUD VARIANCE =     5204.43
                  BAUD SNROUT =   22.7965 =    13.5787 DB


*** TOTAL OVER ALL 5 BAUDS WITH EPSILON =  0.00 ***

            TOTAL NUMBER OF BAUDS =      5
                      MEAN SNROUT =   14.8981 DB
    STANDARD DEVIATION OF SNROUT =    0.7865 DB
```

```
SNROUT VS. DOPPLER TEST -- EPSILON =  0.25

INPUT SNRNB =    31.623 =    15.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES


** OVERALL (REAL + IMAG) STATISTICS FOR THE 1ST BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                    BAUD MEAN =    356.60303
                BAUD VARIANCE =      4178.20
                  BAUD SNROUT =    30.4355 =    14.8338 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 2ND BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                    BAUD MEAN =    357.83740
                BAUD VARIANCE =      4579.19
                  BAUD SNROUT =    27.9630 =    14.4658 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 3RD BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                    BAUD MEAN =    352.04834
                BAUD VARIANCE =      3697.63
                  BAUD SNROUT =    33.5182 =    15.2528 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 4TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                    BAUD MEAN =    358.16406
                BAUD VARIANCE =      4301.95
                  BAUD SNROUT =    29.8194 =    14.7450 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 5TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                    BAUD MEAN =    342.34058
                BAUD VARIANCE =      5904.97
                  BAUD SNROUT =    19.8472 =    12.9770 DB


*** TOTAL OVER ALL 5 BAUDS WITH EPSILON =  0.25 ***


          TOTAL NUMBER OF BAUDS =      5
                    MEAN SNROUT =   14.4549 DB
     STANDARD DEVIATION OF SNROUT =    0.8730 DB
```

```
SNROUT VS. DOPPLER TEST -- EPSILON =  0.50

INPUT SNRNB =    31.623 =    15.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES


** OVERALL (REAL + IMAG) STATISTICS FOR THE 1ST BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                    BAUD MEAN =    351.68213
                BAUD VARIANCE =      5379.54
                  BAUD SNROUT =    22.9909 =    13.6156 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 2ND BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                    BAUD MEAN =    353.07666
                BAUD VARIANCE =      5645.37
                  BAUD SNROUT =    22.0823 =    13.4404 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 3RD BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                    BAUD MEAN =    346.26807
                BAUD VARIANCE =      4283.94
                  BAUD SNROUT =    27.9886 =    14.4698 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 4TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                    BAUD MEAN =    352.39697
                BAUD VARIANCE =      5489.51
                  BAUD SNROUT =    22.6220 =    13.5453 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 5TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                    BAUD MEAN =    335.90625
                BAUD VARIANCE =      7204.71
                  BAUD SNROUT =    15.6610 =    11.9482 DB


*** TOTAL OVER ALL 5 BAUDS WITH EPSILON =  0.50 ***


           TOTAL NUMBER OF BAUDS =      5
                     MEAN SNROUT =   13.4039 DB
    STANDARD DEVIATION OF SNROUT =    0.9112 DB
```

```
SNROUT VS. DOPPLER TEST -- EPSILON =  0.75

INPUT SNRNB =   31.623 =   15.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES


** OVERALL (REAL + IMAG) STATISTICS FOR THE 1ST BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   343.56445
                BAUD VARIANCE =     7197.11
                  BAUD SNROUT =   16.4005 =   12.1486 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 2ND BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   345.20166
                BAUD VARIANCE =     7479.94
                  BAUD SNROUT =   15.9312 =   12.0225 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 3RD BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   336.72485
                BAUD VARIANCE =     5392.54
                  BAUD SNROUT =   21.0260 =   13.2276 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 4TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   342.88135
                BAUD VARIANCE =     7409.56
                  BAUD SNROUT =   15.8670 =   12.0049 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 5TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   325.28076
                BAUD VARIANCE =     9073.28
                  BAUD SNROUT =   11.6614 =   10.6675 DB


*** TOTAL OVER ALL 5 BAUDS WITH EPSILON =  0.75 ***


        TOTAL NUMBER OF BAUDS =     5
                  MEAN SNROUT =   12.0142 DB
  STANDARD DEVIATION OF SNROUT =    0.9088 DB
```

```
SNROUT VS. DOPPLER TEST -- EPSILON =  1.00

INPUT SNRNB =    31.623 =    15.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES


** OVERALL (REAL + IMAG) STATISTICS FOR THE 1ST BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   332.46948
                BAUD VARIANCE =     9581.14
                  BAUD SNROUT =   11.5368 =    10.6209 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 2ND BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   334.46362
                BAUD VARIANCE =    10027.16
                  BAUD SNROUT =   11.1563 =    10.4752 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 3RD BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   323.73706
                BAUD VARIANCE =     7001.29
                  BAUD SNROUT =   14.9695 =    11.7521 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 4TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   329.95630
                BAUD VARIANCE =    10013.46
                  BAUD SNROUT =   10.8725 =    10.3633 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 5TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   310.86450
                BAUD VARIANCE =    11450.02
                  BAUD SNROUT =    8.4399 =     9.2634 DB


*** TOTAL OVER ALL 5 BAUDS WITH EPSILON =  1.00 ***


          TOTAL NUMBER OF BAUDS =      5
                    MEAN SNROUT =   10.4949 DB
     STANDARD DEVIATION OF SNROUT =    0.8847 DB
```

```
SNROUT VS. DOPPLER TEST -- EPSILON =  1.25

INPUT SNRNB =   31.623 =   15.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES


** OVERALL (REAL + IMAG) STATISTICS FOR THE 1ST BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   318.38794
                BAUD VARIANCE =    12548.15
                  BAUD SNROUT =    8.0786 =    9.0733 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 2ND BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   320.88208
                BAUD VARIANCE =    13305.20
                  BAUD SNROUT =    7.7387 =    8.8867 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 3RD BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   307.26807
                BAUD VARIANCE =     9126.79
                  BAUD SNROUT =   10.3447 =   10.1472 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 4TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   313.63037
                BAUD VARIANCE =    13315.13
                  BAUD SNROUT =    7.3874 =    8.6849 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 5TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   292.66162
                BAUD VARIANCE =    14353.81
                  BAUD SNROUT =    5.9671 =    7.7576 DB


*** TOTAL OVER ALL 5 BAUDS WITH EPSILON =  1.25 ***


        TOTAL NUMBER OF BAUDS =      5
                  MEAN SNROUT =    8.9099 DB
   STANDARD DEVIATION OF SNROUT =    0.8568 DB
```

```
SNROUT VS. DOPPLER TEST -- EPSILON =  1.50

INPUT SNRNB =    31.623 =    15.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES


** OVERALL (REAL + IMAG) STATISTICS FOR THE 1ST BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                    BAUD MEAN =    301.64111
                BAUD VARIANCE =     16039.55
                  BAUD SNROUT =     5.6727 =    7.5379 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 2ND BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                    BAUD MEAN =    304.77563
                BAUD VARIANCE =     17242.49
                  BAUD SNROUT =     5.3872 =    7.3136 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 3RD BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                    BAUD MEAN =    287.72412
                BAUD VARIANCE =     11751.02
                  BAUD SNROUT =     7.0449 =    8.4788 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 4TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                    BAUD MEAN =    294.33276
                BAUD VARIANCE =     17252.69
                  BAUD SNROUT =     5.0213 =    7.0082 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 5TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                    BAUD MEAN =    271.16650
                BAUD VARIANCE =     17716.52
                  BAUD SNROUT =     4.1504 =    6.1809 DB


*** TOTAL OVER ALL 5 BAUDS WITH EPSILON =  1.50 ***

           TOTAL NUMBER OF BAUDS =      5
                     MEAN SNROUT =    7.3039 DB
    STANDARD DEVIATION OF SNROUT =    0.8342 DB
```

```
SNROUT VS. DOPPLER TEST -- EPSILON =  1.75

INPUT SNRNB =    31.623 =    15.000 DB

BAUD TYPE 3:   KX = 1024 SAMPLE POINTS; K =  64 TONES


** OVERALL (REAL + IMAG) STATISTICS FOR THE 1ST BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   282.71875
                BAUD VARIANCE =    19969.26
                  BAUD SNROUT =    4.0026 =    6.0235 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 2ND BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   286.64087
                BAUD VARIANCE =    21735.70
                  BAUD SNROUT =    3.7801 =    5.7750 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 3RD BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   265.68335
                BAUD VARIANCE =    14806.48
                  BAUD SNROUT =    4.7673 =    6.7828 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 4TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   272.69653
                BAUD VARIANCE =    21720.69
                  BAUD SNROUT =    3.4236 =    5.3449 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 5TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   247.10403
                BAUD VARIANCE =    21451.55
                  BAUD SNROUT =    2.8464 =    4.5430 DB


*** TOTAL OVER ALL 5 BAUDS WITH EPSILON =  1.75 ***


        TOTAL NUMBER OF BAUDS =      5
                  MEAN SNROUT =    5.6938 DB
   STANDARD DEVIATION OF SNROUT =    0.8287 DB
```

```
SNROUT VS. DOPPLER TEST -- EPSILON =  2.00

INPUT SNRNB =    31.623 =    15.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES


** OVERALL (REAL + IMAG) STATISTICS FOR THE 1ST BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   261.53735
                BAUD VARIANCE =    24362.90
                  BAUD SNROUT =    2.8076 =    4.4834 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 2ND BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   266.46338
                BAUD VARIANCE =    26814.79
                  BAUD SNROUT =    2.6479 =    4.2290 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 3RD BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   242.98599
                BAUD VARIANCE =    18343.12
                  BAUD SNROUT =    3.2188 =    5.0769 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 4TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   248.73459
                BAUD VARIANCE =    26755.45
                  BAUD SNROUT =    2.3124 =    3.6406 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 5TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   239.01096
                BAUD VARIANCE =    25585.32
                  BAUD SNROUT =    2.2328 =    3.4884 DB


*** TOTAL OVER ALL 5 BAUDS WITH EPSILON =  2.00 ***


           TOTAL NUMBER OF BAUDS =      5
                     MEAN SNROUT =    4.1837 DB
   STANDARD DEVIATION OF SNROUT =    0.6458 DB
```

```
SNROUT VS. DOPPLER TEST -- EPSILON =  2.25

INPUT SNRNB =    31.623 =    15.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES


** OVERALL (REAL + IMAG) STATISTICS FOR THE 1ST BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                    BAUD MEAN =    243.64471
                BAUD VARIANCE =     29136.31
                  BAUD SNROUT =     2.0374 =     3.0908 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 2ND BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                    BAUD MEAN =    248.93130
                BAUD VARIANCE =     32359.91
                  BAUD SNROUT =     1.9149 =     2.8215 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 3RD BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                    BAUD MEAN =    240.99722
                BAUD VARIANCE =     22283.86
                  BAUD SNROUT =     2.6064 =     4.1603 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 4TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                    BAUD MEAN =    230.72388
                BAUD VARIANCE =     32238.76
                  BAUD SNROUT =     1.6512 =     2.1781 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 5TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                    BAUD MEAN =    244.09976
                BAUD VARIANCE =     30041.91
                  BAUD SNROUT =     1.9834 =     2.9741 DB


*** TOTAL OVER ALL 5 BAUDS WITH EPSILON =  2.25 ***


        TOTAL NUMBER OF BAUDS =      5
                  MEAN SNROUT =    3.0450 DB
  STANDARD DEVIATION OF SNROUT =    0.7163 DB
```

```
SNROUT VS. DOPPLER TEST -- EPSILON =  2.50

INPUT SNRNB =    31.623 =    15.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES


** OVERALL (REAL + IMAG) STATISTICS FOR THE 1ST BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   240.04703
                BAUD VARIANCE =    34182.69
                  BAUD SNROUT =    1.6857 =    2.2679 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 2ND BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   234.67413
                BAUD VARIANCE =    38249.63
                  BAUD SNROUT =    1.4398 =    1.5830 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 3RD BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   254.86404
                BAUD VARIANCE =    26564.81
                  BAUD SNROUT =    2.4452 =    3.8831 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 4TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   228.89236
                BAUD VARIANCE =    38044.78
                  BAUD SNROUT =    1.3771 =    1.3897 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 5TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   255.39224
                BAUD VARIANCE =    34706.46
                  BAUD SNROUT =    1.8793 =    2.7400 DB


*** TOTAL OVER ALL 5 BAUDS WITH EPSILON =  2.50 ***


          TOTAL NUMBER OF BAUDS =     5
                    MEAN SNROUT =    2.3727 DB
  STANDARD DEVIATION OF SNROUT =    1.0021 DB
```

```
SNROUT VS. DOPPLER TEST -- EPSILON =  2.75

INPUT SNRNB =    31.623 =    15.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES


** OVERALL (REAL + IMAG) STATISTICS FOR THE 1ST BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                   BAUD MEAN =    250.07709
               BAUD VARIANCE =     39538.09
                 BAUD SNROUT =     1.5817 =     1.9913 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 2ND BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                   BAUD MEAN =    225.95108
               BAUD VARIANCE =     44515.95
                 BAUD SNROUT =     1.1469 =     0.5951 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 3RD BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                   BAUD MEAN =    265.65649
               BAUD VARIANCE =     31226.82
                 BAUD SNROUT =     2.2600 =     3.5411 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 4TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                   BAUD MEAN =    236.69147
               BAUD VARIANCE =     44222.02
                 BAUD SNROUT =     1.2669 =     1.0273 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 5TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                   BAUD MEAN =    262.79248
               BAUD VARIANCE =     39631.13
                 BAUD SNROUT =     1.7426 =     2.4119 DB


*** TOTAL OVER ALL 5 BAUDS WITH EPSILON =  2.75 ***


        TOTAL NUMBER OF BAUDS =      5
                  MEAN SNROUT =     1.9133 DB
  STANDARD DEVIATION OF SNROUT =     1.1648 DB
```

B. INPUT SNR = 5 dB

```
SNROUT VS. DOPPLER TEST -- EPSILON =  0.00

INPUT SNRNB =     3.162 =     5.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES


** OVERALL (REAL + IMAG) STATISTICS FOR THE 1ST BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   348.85937
                BAUD VARIANCE =    36188.43
                  BAUD SNROUT =    3.3630 =    5.2673 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 2ND BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   352.66479
                BAUD VARIANCE =    43009.19
                  BAUD SNROUT =    2.8918 =    4.6116 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 3RD BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   335.33081
                BAUD VARIANCE =    36318.57
                  BAUD SNROUT =    3.0961 =    4.9082 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 4TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   354.62695
                BAUD VARIANCE =    38677.65
                  BAUD SNROUT =    3.2515 =    5.1208 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 5TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   305.20776
                BAUD VARIANCE =    52039.11
                  BAUD SNROUT =    1.7900 =    2.5286 DB


*** TOTAL OVER ALL 5 BAUDS WITH EPSILON =  0.00 ***


          TOTAL NUMBER OF BAUDS =      5
                    MEAN SNROUT =    4.4873 DB
   STANDARD DEVIATION OF SNROUT =    1.1224 DB
```

```
SNROUT VS. DOPPLER TEST -- EPSILON =  0.25

INPUT SNRNB =    3.162 =    5.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES


** OVERALL (REAL + IMAG) STATISTICS FOR THE 1ST BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   347.25366
                BAUD VARIANCE =    37339.82
                  BAUD SNROUT =    3.2294 =    5.0912 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 2ND BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   351.10767
                BAUD VARIANCE =    43143.09
                  BAUD SNROUT =    2.8574 =    4.5597 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 3RD BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   333.41895
                BAUD VARIANCE =    35979.64
                  BAUD SNROUT =    3.0898 =    4.8992 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 4TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   352.74438
                BAUD VARIANCE =    39246.14
                  BAUD SNROUT =    3.1705 =    5.0112 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 5TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   303.09644
                BAUD VARIANCE =    53554.99
                  BAUD SNROUT =    1.7154 =    2.3436 DB


*** TOTAL OVER ALL 5 BAUDS WITH EPSILON =  0.25 ***


        TOTAL NUMBER OF BAUDS =     5
                  MEAN SNROUT =    4.3810 DB
 STANDARD DEVIATION OF SNROUT =    1.1568 DB
```

```
SNROUT VS. DOPPLER TEST -- EPSILON =  0.50

INPUT SNRNB =     3.162 =     5.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES


** OVERALL (REAL + IMAG) STATISTICS FOR THE 1ST BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                   BAUD MEAN =    342.34521
               BAUD VARIANCE =     39210.31
                 BAUD SNROUT =     2.9890 =     4.7553 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 2ND BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                   BAUD MEAN =    346.34448
               BAUD VARIANCE =     44183.36
                 BAUD SNROUT =     2.7149 =     4.3376 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 3RD BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                   BAUD MEAN =    327.63818
               BAUD VARIANCE =     36156.82
                 BAUD SNROUT =     2.9689 =     4.7260 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 4TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                   BAUD MEAN =    346.97949
               BAUD VARIANCE =     40537.41
                 BAUD SNROUT =     2.9700 =     4.7275 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 5TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                   BAUD MEAN =    296.65332
               BAUD VARIANCE =     55526.02
                 BAUD SNROUT =     1.5849 =     2.0000 DB


*** TOTAL OVER ALL 5 BAUDS WITH EPSILON =  0.50 ***

           TOTAL NUMBER OF BAUDS =       5
                     MEAN SNROUT =     4.1093 DB
    STANDARD DEVIATION OF SNROUT =     1.1917 DB
```

```
SNROUT VS. DOPPLER TEST -- EPSILON =  0.75

INPUT SNRNB =     3.162 =     5.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES


** OVERALL (REAL + IMAG) STATISTICS FOR THE 1ST BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                   BAUD MEAN =   334.21777
               BAUD VARIANCE =    41755.36
                 BAUD SNROUT =    2.6751 =    4.2735 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 2ND BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                   BAUD MEAN =   338.46997
               BAUD VARIANCE =    46133.04
                 BAUD SNROUT =    2.4833 =    3.9503 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 3RD BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                   BAUD MEAN =   318.09814
               BAUD VARIANCE =    36878.21
                 BAUD SNROUT =    2.7438 =    4.3835 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 4TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                   BAUD MEAN =   337.46533
               BAUD VARIANCE =    42530.41
                 BAUD SNROUT =    2.6777 =    4.2776 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 5TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                   BAUD MEAN =   286.04077
               BAUD VARIANCE =    57909.20
                 BAUD SNROUT =    1.4129 =    1.5011 DB


*** TOTAL OVER ALL 5 BAUDS WITH EPSILON =  0.75 ***


        TOTAL NUMBER OF BAUDS =      5
                  MEAN SNROUT =    3.6772 DB
  STANDARD DEVIATION OF SNROUT =    1.2273 DB
```

```
SNROUT VS. DOPPLER TEST -- EPSILON =  1.00

INPUT SNRNB =    3.162 =    5.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES


** OVERALL (REAL + IMAG) STATISTICS FOR THE 1ST BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   323.12573
                BAUD VARIANCE =    44902.68
                  BAUD SNROUT =    2.3253 =    3.6647 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 2ND BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   327.73608
                BAUD VARIANCE =    48904.04
                  BAUD SNROUT =    2.1964 =    3.4170 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 3RD BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   305.10498
                BAUD VARIANCE =    38135.35
                  BAUD SNROUT =    2.4410 =    3.8757 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 4TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   324.53516
                BAUD VARIANCE =    45177.82
                  BAUD SNROUT =    2.3313 =    3.6760 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 5TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   271.62476
                BAUD VARIANCE =    60591.47
                  BAUD SNROUT =    1.2177 =    0.8553 DB


*** TOTAL OVER ALL 5 BAUDS WITH EPSILON =  1.00 ***


          TOTAL NUMBER OF BAUDS =      5
                    MEAN SNROUT =    3.0977 DB
    STANDARD DEVIATION OF SNROUT =    1.2641 DB
```

```
SNROUT VS. DOPPLER TEST -- EPSILON =  1.25

INPUT SNRNB =     3.162 =    5.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES


** OVERALL (REAL + IMAG) STATISTICS FOR THE 1ST BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   309.05103
                BAUD VARIANCE =    48664.34
                  BAUD SNROUT =    1.9627 =    2.9285 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 2ND BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   314.15283
                BAUD VARIANCE =    52524.69
                  BAUD SNROUT =    1.8790 =    2.7392 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 3RD BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   288.63892
                BAUD VARIANCE =    39937.87
                  BAUD SNROUT =    2.0861 =    3.1932 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 4TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   308.20581
                BAUD VARIANCE =    48482.35
                  BAUD SNROUT =    1.9593 =    2.9210 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 5TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   253.42087
                BAUD VARIANCE =    63620.02
                  BAUD SNROUT =    1.0095 =    0.0409 DB


*** TOTAL OVER ALL 5 BAUDS WITH EPSILON =  1.25 ***


        TOTAL NUMBER OF BAUDS =     5
                  MEAN SNROUT =    2.3646 DB
   STANDARD DEVIATION OF SNROUT =    1.3090 DB
```

```
SNROUT VS. DOPPLER TEST -- EPSILON =  1.50

INPUT SNRNB =    3.162 =    5.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES


** OVERALL (REAL + IMAG) STATISTICS FOR THE 1ST BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   292.29761
               BAUD VARIANCE =     52952.92
                 BAUD SNROUT =     1.6135 =    2.0776 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 2ND BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   298.04663
               BAUD VARIANCE =     56898.22
                 BAUD SNROUT =     1.5612 =    1.9347 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 3RD BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   269.08667
               BAUD VARIANCE =    42304.40
                 BAUD SNROUT =     1.7116 =    2.3340 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 4TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   288.91211
               BAUD VARIANCE =     52405.19
                 BAUD SNROUT =     1.5928 =    2.0216 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 5TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =   128
                    BAUD MEAN =   237.78751
               BAUD VARIANCE =     66898.56
                 BAUD SNROUT =     0.8452 =   -0.7304 DB


*** TOTAL OVER ALL 5 BAUDS WITH EPSILON =  1.50 ***


          TOTAL NUMBER OF BAUDS =      5
                    MEAN SNROUT =    1.5275 DB
   STANDARD DEVIATION OF SNROUT =    1.2709 DB
```

```
SNROUT VS. DOPPLER TEST -- EPSILON =  1.75

INPUT SNRNB =     3.162 =     5.000 DB

BAUD TYPE 3:  KX = 1024 SAMPLE POINTS; K =  64 TONES


** OVERALL (REAL + IMAG) STATISTICS FOR THE 1ST BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                   BAUD MEAN =    278.15869
               BAUD VARIANCE =     57652.27
                 BAUD SNROUT =     1.3420 =     1.2777 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 2ND BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                   BAUD MEAN =    288.96216
               BAUD VARIANCE =     61909.75
                 BAUD SNROUT =     1.3487 =     1.2992 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 3RD BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                   BAUD MEAN =    247.04657
               BAUD VARIANCE =     45172.92
                 BAUD SNROUT =     1.3511 =     1.3068 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 4TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                   BAUD MEAN =    267.27612
               BAUD VARIANCE =     56809.34
                 BAUD SNROUT =     1.2575 =     0.9950 DB

** OVERALL (REAL + IMAG) STATISTICS FOR THE 5TH BAUD **

   TOTAL NUMBER OF POINTS, 2K =    128
                   BAUD MEAN =    241.30634
               BAUD VARIANCE =     70345.50
                 BAUD SNROUT =     0.8278 =    -0.8210 DB


*** TOTAL OVER ALL 5 BAUDS WITH EPSILON =  1.75 ***

          TOTAL NUMBER OF BAUDS =      5
                    MEAN SNROUT =     0.8115 DB
   STANDARD DEVIATION OF SNROUT =     0.9218 DB
```

APPENDIX E. STATISTICS OF THE DOPPLER ESTIMATION ALGORITHM

A. INPUT SNR = 10 dB

```
ALPHA-HAT VS. ALPHA -- INPUT SNR = 10 DB
  BAUD TYPE 3:  KX = 1024 SAMPLE POINTS;  K = 64 TONES


**  EPSILON = 0.0        DELTA-ALPHA = 0.000376506

    LL   ALPHA           ALPHA-HAT      EPSILON-HAT

    1    0.000           0.00008162     0.21678060
    2    0.000          -0.00005518    -0.14657104
    3    0.000           0.00000018     0.00046881
    4    0.000          -0.00029124    -0.77353448
    5    0.000          -0.00000678    -0.01801626

          NUMBER OF BAUDS =           5
      MEAN OF EPSILON-HAT = -0.144174457
  VARIANCE OF EPSILON-HAT =  0.140806437


**  EPSILON = 0.25       DELTA-ALPHA = 0.000376506

    LL   ALPHA           ALPHA-HAT      EPSILON-HAT

    1    0.000094128     0.00017936     0.47636849
    2    0.000094128     0.00003786     0.10056025
    3    0.000094128     0.00011023     0.29278034
    4    0.000094128    -0.00020184    -0.53608972
    5    0.000094128     0.00009492     0.25209653

          NUMBER OF BAUDS =           5
      MEAN OF EPSILON-HAT =  0.117143154
  VARIANCE OF EPSILON-HAT =  0.151272893


**  EPSILON = 0.50       DELTA-ALPHA = 0.000376506

    LL   ALPHA           ALPHA-HAT      EPSILON-HAT

    1    0.000188255    -0.00011252    -0.29886585
    2    0.000188255     0.00013242     0.35169941
    3    0.000188255     0.00021961     0.58327287
    4    0.000188255     0.00011711     0.31104386
    5    0.000188255     0.00019830     0.52669251

          NUMBER OF BAUDS =           5
      MEAN OF EPSILON-HAT =  0.294768512
  VARIANCE OF EPSILON-HAT =  0.123232782
```

ALPHA-HAT VS. ALPHA -- INPUT SNR = 10 DB
BAUD TYPE 3: KX = 1024 SAMPLE POINTS; K = 64 TONES

** EPSILON = 0.75 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000282383	-0.00024254	-0.64418107
2	0.000282383	0.00003668	0.09741002
3	0.000282383	0.00013307	0.35344487
4	0.000282383	0.00021555	0.57250100
5	0.000282383	0.00030271	0.80399001

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 0.236632884
VARIANCE OF EPSILON-HAT = 0.310890436

** EPSILON = 1.00 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000376506	-0.00034564	-0.91803193
2	0.000376506	0.00013396	0.35578859
3	0.000376506	0.00023758	0.63100237
4	0.000376506	0.00031679	0.84140372
5	0.000376506	0.00019155	0.50875187

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 0.283782721
VARIANCE OF EPSILON-HAT = 0.482913494

** EPSILON = 1.25 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000470638	-0.00088145	-2.34113503
2	0.000470638	0.00023501	0.62418330
3	0.000470638	0.00034109	0.90593851
4	0.000470638	0.00023151	0.61489588
5	0.000470638	-0.00013302	-0.35329860

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = -0.109883070
VARIANCE OF EPSILON-HAT = 1.78344536

ALPHA-HAT VS. ALPHA -- INPUT SNR = 10 DB
BAUD TYPE 3: KX = 1024 SAMPLE POINTS; K = 64 TONES

** EPSILON = 1.50 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000564765	-0.00100695	-2.67446518
2	0.000564765	-0.00051077	-1.35661030
3	0.000564765	-0.00061805	-1.64155102
4	0.000564765	-0.00006197	-0.16459131
5	0.000564765	-0.00002642	-0.07016611

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = -1.18147659
VARIANCE OF EPSILON-HAT = 1.18510342

B. INPUT SNR = 15 dB

ALPHA-HAT VS. ALPHA -- INPUT SNR = 15 DB
BAUD TYPE 3: KX = 1024 SAMPLE POINTS; K = 64 TONES

** EPSILON = 0.0 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000	0.00004005	0.10637712
2	0.000	-0.00002999	-0.07964146
3	0.000	-0.00000758	-0.02012977
4	0.000	-0.00003488	-0.09264153
5	0.000	0.00000226	0.00600086

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = -0.160069466E-01
VARIANCE OF EPSILON-HAT = 0.635034963E-02

** EPSILON = 0.25 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000094128	0.00013718	0.36434567
2	0.000094128	0.00006437	0.17096901
3	0.000094128	0.00009453	0.25108421
4	0.000094128	0.00005696	0.15127569
5	0.000094128	0.00010090	0.26797980

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 0.241130829
VARIANCE OF EPSILON-HAT = 0.724961236E-02

** EPSILON = 0.50 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000188255	0.00023408	0.62171990
2	0.000188255	0.00016005	0.42509770
3	0.000188255	0.00019705	0.52335626
4	0.000188255	0.00015115	0.40144742
5	0.000188255	0.00020043	0.53233200

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 0.500790179
VARIANCE OF EPSILON-HAT = 0.793160871E-02

ALPHA-HAT VS. ALPHA -- INPUT SNR = 15 DB
BAUD TYPE 3: KX = 1024 SAMPLE POINTS; K = 64 TONES

** EPSILON = 0.75 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000282383	0.00033001	0.87650335
2	0.000282383	0.00025643	0.68107283
3	0.000282383	0.00029901	0.79417539
4	0.000282383	0.00024693	0.65585577
5	0.000282383	0.00029999	0.79678440

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 0.760878146
VARIANCE OF EPSILON-HAT = 0.829143077E-02

** EPSILON = 0.80 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000301205	0.00034829	0.92506492
2	0.000301205	0.00027502	0.73044205
3	0.000301205	0.00031849	0.84590751
4	0.000301205	0.00026549	0.70512855
5	0.000301205	0.00031912	0.84758091

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 0.810824394
VARIANCE OF EPSILON-HAT = 0.831642002E-02

** EPSILON = 0.85 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000320030	0.00036756	0.97623181
2	0.000320030	0.00029466	0.78261632
3	0.000320030	0.00033904	0.90049165
4	0.000320030	0.00028515	0.75734794
5	0.000320030	0.00033927	0.90109152

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 0.863555133
VARIANCE OF EPSILON-HAT = 0.832509249E-02

```
ALPHA-HAT VS. ALPHA -- INPUT SNR = 15 DB
  BAUD TYPE 3:  KX = 1024 SAMPLE POINTS;  K = 64 TONES


**  EPSILON = 0.90       DELTA-ALPHA = 0.000376506

    LL   ALPHA           ALPHA-HAT     EPSILON-HAT

    1    0.000338855     0.00038678    1.02729702
    2    0.000338855     0.00031433    0.83485985
    3    0.000338855     0.00035951    0.95485568
    4    0.000338855     0.00030481    0.80957907
    5    0.000338855     0.00035939    0.95453286

        NUMBER OF BAUDS =           5
      MEAN OF EPSILON-HAT =  0.916224658
    VARIANCE OF EPSILON-HAT =  0.832261145E-02


**  EPSILON = 0.95       DELTA-ALPHA = 0.000376506

    LL   ALPHA           ALPHA-HAT     EPSILON-HAT

    1    0.000357681     0.00020686    0.54943258
    2    0.000357681     0.00033398    0.88705266
    3    0.000357681     0.00037992    1.00906944
    4    0.000357681     0.00032449    0.86183619
    5    0.000357681     0.00037949    1.00792885

        NUMBER OF BAUDS =           5
      MEAN OF EPSILON-HAT =  0.863063574
    VARIANCE OF EPSILON-HAT =  0.353112072E-01


**  EPSILON = 1.00       DELTA-ALPHA = 0.000376506

    LL   ALPHA           ALPHA-HAT     EPSILON-HAT

    1    0.000376506     0.00003566    0.09470624
    2    0.000376506     0.00016103    0.42768973
    3    0.000376506     0.00020522    0.54507101
    4    0.000376506     0.00034329    0.91177434
    5    0.000376506     0.00039861    1.05871677

        NUMBER OF BAUDS =           5
      MEAN OF EPSILON-HAT =  0.607591391
    VARIANCE OF EPSILON-HAT =  0.148841441
```

ALPHA-HAT VS. ALPHA -- INPUT SNR = 15 DB
BAUD TYPE 3: KX = 1024 SAMPLE POINTS; K = 64 TONES

** EPSILON = 1.25 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000470638	-0.00049591	-1.31713200
2	0.000470638	0.00025919	0.68840146
3	0.000470638	0.00030580	0.81219983
4	0.000470638	0.00005479	0.14553374
5	0.000470638	0.00028259	0.75056285

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 0.215912998
VARIANCE OF EPSILON-HAT = 0.804957628

** EPSILON = 1.50 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000564765	-0.00082413	-2.18889141
2	0.000564765	-0.00046605	-1.23783207
3	0.000564765	-0.00020983	-0.55731559
4	0.000564765	-0.00024733	-0.65690029
5	0.000564765	-0.00004868	-0.12930280

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = -0.954047918
VARIANCE OF EPSILON-HAT = 0.632816792

C. INPUT SNR = 20 dB

```
ALPHA-HAT VS. ALPHA -- INPUT SNR = 20 DB
  BAUD TYPE 3:  KX = 1024 SAMPLE POINTS;  K = 64 TONES


**  EPSILON = 0.0          DELTA-ALPHA = 0.000376506

    LL   ALPHA             ALPHA-HAT      EPSILON-HAT

    1    0.000              0.00002055     0.05457596
    2    0.000             -0.00001621    -0.04305860
    3    0.000             -0.00000631    -0.01675819
    4    0.000             -0.00001915    -0.05085765
    5    0.000              0.00000311     0.00826014

            NUMBER OF BAUDS =            5
        MEAN OF EPSILON-HAT = -0.956766680E-02
    VARIANCE OF EPSILON-HAT =  0.182760879E-02


**  EPSILON = 0.25         DELTA-ALPHA = 0.000376506

    LL   ALPHA             ALPHA-HAT      EPSILON-HAT

    1    0.000094128       0.00011643     0.30924392
    2    0.000094128       0.00007815     0.20756477
    3    0.000094128       0.00009204     0.24444658
    4    0.000094128       0.00007348     0.19517177
    5    0.000094128       0.00009959     0.26451528

            NUMBER OF BAUDS =            5
        MEAN OF EPSILON-HAT =  0.244188309
    VARIANCE OF EPSILON-HAT =  0.209734496E-02


**  EPSILON = 0.50         DELTA-ALPHA = 0.000376506

    LL   ALPHA             ALPHA-HAT      EPSILON-HAT

    1    0.000188255       0.00021262     0.56471968
    2    0.000188255       0.00017358     0.46102297
    3    0.000188255       0.00019098     0.50724143
    4    0.000188255       0.00016762     0.44520897
    5    0.000188255       0.00019673     0.52252698

            NUMBER OF BAUDS =            5
        MEAN OF EPSILON-HAT =  0.500143766
    VARIANCE OF EPSILON-HAT =  0.231742300E-02
```

ALPHA-HAT VS. ALPHA -- INPUT SNR = 20 DB
BAUD TYPE 3: KX = 1024 SAMPLE POINTS; K = 64 TONES

** EPSILON = 0.75   DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000282383	0.00030833	0.81892306
2	0.000282383	0.00026935	0.71539086
3	0.000282383	0.00028965	0.76931149
4	0.000282383	0.00026252	0.69726127
5	0.000282383	0.00029374	0.78016865

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 0.756210685
VARIANCE OF EPSILON-HAT = 0.245493464E-02

** EPSILON = 1.00   DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000376506	0.00040266	1.06947517
2	0.000376506	0.00036461	0.96840972
3	0.000376506	0.00038703	1.02794170
4	0.000376506	0.00035726	0.94887573
5	0.000376506	0.00038970	1.03504181

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 1.00994873
VARIANCE OF EPSILON-HAT = 0.248805061E-02

** EPSILON = 1.05   DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000395336	0.00042184	1.12041664
2	0.000395336	0.00038408	1.02010632
3	0.000395336	0.00040684	1.08056164
4	0.000395336	0.00037666	1.00041580
5	0.000395336	0.00040925	1.08697891

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 1.06169510
VARIANCE OF EPSILON-HAT = 0.248205289E-02

ALPHA-HAT VS. ALPHA -- INPUT SNR = 20 DB
BAUD TYPE 3: KX = 1024 SAMPLE POINTS; K = 64 TONES

** EPSILON = 1.10 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000414161	0.00044105	1.17141533
2	0.000414161	0.00021188	0.56274819
3	0.000414161	0.00042667	1.13323879
4	0.000414161	0.00039613	1.05211163
5	0.000414161	0.00042883	1.13897419

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 1.01169682
VARIANCE OF EPSILON-HAT = 0.649175048E-01

** EPSILON = 1.15 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000432987	0.00026110	0.69347852
2	0.000432987	0.00023134	0.61445159
3	0.000432987	0.00025232	0.67015254
4	0.000432987	0.00021900	0.58167678
5	0.000432987	0.00044832	1.19074154

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 0.750099897
VARIANCE OF EPSILON-HAT = 0.626323223E-01

** EPSILON = 1.20 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000451812	0.00008400	0.22311223
2	0.000451812	0.00024993	0.66380346
3	0.000451812	0.00027113	0.72011048
4	0.000451812	0.00004699	0.12480402
5	0.000451812	0.00046693	1.24015808

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 0.594397545
VARIANCE OF EPSILON-HAT = 0.198999524

ALPHA-HAT VS. ALPHA -- INPUT SNR = 20 DB
BAUD TYPE 3: KX = 1024 SAMPLE POINTS; K = 64 TONES

** EPSILON = 1.25 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000470638	0.00010312	0.27389467
2	0.000470638	0.00026947	0.71572357
3	0.000470638	0.00010148	0.26952112
4	0.000470638	0.00006651	0.17663908
5	0.000470638	0.00048646	1.29204941

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 0.545565367
VARIANCE OF EPSILON-HAT = 0.218075991

** EPSILON = 1.50 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000564765	-0.00062383	-1.65688896
2	0.000564765	-0.00024093	-0.63990915
3	0.000564765	-0.00022707	-0.60310274
4	0.000564765	-0.00023840	-0.63318038
5	0.000564765	-0.00006303	-0.16741729

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = -0.740099311
VARIANCE OF EPSILON-HAT = 0.302176237

D. INPUT SNR = 40 dB

ALPHA-HAT VS. ALPHA -- INPUT SNR = 40 DB
BAUD TYPE 3: KX = 1024 SAMPLE POINTS; K = 64 TONES

** EPSILON = 0.0 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000	0.00000226	0.00601395
2	0.000	-0.00000109	-0.00289558
3	0.000	-0.00000038	-0.00100686
4	0.000	-0.00000142	-0.00376268
5	0.000	0.00000092	0.00243571

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 0.156908704E-03
VARIANCE OF EPSILON-HAT = 0.163832447E-04

** EPSILON = 0.25 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000094128	0.00009623	0.25558215
2	0.000094128	0.00009274	0.24631453
3	0.000094128	0.00009378	0.24908829
4	0.000094128	0.00009219	0.24485534
5	0.000094128	0.00009487	0.25196874

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 0.249561667
VARIANCE OF EPSILON-HAT = 0.187394326E-04

** EPSILON = 0.50 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000188255	0.00019089	0.50700271
2	0.000188255	0.00018733	0.49755794
3	0.000188255	0.00018857	0.50083911
4	0.000188255	0.00018658	0.49555242
5	0.000188255	0.00018942	0.50309473

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 0.500809073
VARIANCE OF EPSILON-HAT = 0.204471289E-04

ALPHA-HAT VS. ALPHA -- INPUT SNR = 40 DB
BAUD TYPE 3: KX = 1024 SAMPLE POINTS; K = 64 TONES

** EPSILON = 0.75   DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000282383	0.00028547	0.75821120
2	0.000282383	0.00028194	0.74884433
3	0.000282383	0.00028319	0.75216144
4	0.000282383	0.00028101	0.74635839
5	0.000282383	0.00028383	0.75386328

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 0.751887321
VARIANCE OF EPSILON-HAT = 0.209499267E-04

** EPSILON = 1.00   DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000376506	0.00037910	1.00688934
2	0.000376506	0.00037569	0.99783307
3	0.000376506	0.00037675	1.00063419
4	0.000376506	0.00037461	0.99496496
5	0.000376506	0.00037728	1.00205612

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 1.00047493
VARIANCE OF EPSILON-HAT = 0.202523515E-04

** EPSILON = 1.05   DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000395336	0.00039818	1.05757332
2	0.000395336	0.00039480	1.04860115
3	0.000395336	0.00039580	1.05124378
4	0.000395336	0.00039370	1.04568005
5	0.000395336	0.00039634	1.05267429

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 1.05115414
VARIANCE OF EPSILON-HAT = 0.200020440E-04

ALPHA-HAT VS. ALPHA -- INPUT SNR = 40 DB
BAUD TYPE 3: KX = 1024 SAMPLE POINTS; K = 64 TONES

** EPSILON = 1.10 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000414161	0.00041730	1.10836124
2	0.000414161	0.00041396	1.09947109
3	0.000414161	0.00041488	1.10192490
4	0.000414161	0.00041284	1.09649086
5	0.000414161	0.00041541	1.10333538

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 1.10191631
VARIANCE OF EPSILON-HAT = 0.197413901E-04

** EPSILON = 1.15 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000432987	0.00043634	1.15891647
2	0.000432987	0.00043304	1.15016556
3	0.000432987	0.00043389	1.15240288
4	0.000432987	0.00023536	0.62512481
5	0.000432987	0.00043442	1.15381145

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 1.04808331
VARIANCE OF EPSILON-HAT = 0.559149086E-01

** EPSILON = 1.20 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000451812	0.00045451	1.20717335
2	0.000451812	0.00045124	1.19849777
3	0.000451812	0.00026262	0.69750923
4	0.000451812	0.00006299	0.16730273
5	0.000451812	0.00045256	1.20199013

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 0.894494414
VARIANCE OF EPSILON-HAT = 0.213087618

ALPHA-HAT VS. ALPHA -- INPUT SNR = 40 DB
BAUD TYPE 3: KX = 1024 SAMPLE POINTS; K = 64 TONES

** EPSILON = 1.25 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000470638	0.00047359	1.25785255
2	0.000470638	0.00008576	0.22777945
3	0.000470638	0.00028165	0.74806517
4	0.000470638	-0.00011694	-0.31059778
5	0.000470638	0.00047162	1.25261021

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = 0.635141730
VARIANCE OF EPSILON-HAT = 0.460538387

** EPSILON = 1.50 DELTA-ALPHA = 0.000376506

LL	ALPHA	ALPHA-HAT	EPSILON-HAT
1	0.000564765	-0.00044042	-1.16975403
2	0.000564765	-0.00001852	-0.04919485
3	0.000564765	-0.00024438	-0.64908123
4	0.000564765	-0.00022513	-0.59793478
5	0.000564765	-0.00006345	-0.16852963

NUMBER OF BAUDS = 5
MEAN OF EPSILON-HAT = -0.526898742
VARIANCE OF EPSILON-HAT = 0.197466671

APPENDIX F. THE SIMULATION CODE: RXSIM

```
C  THIS SIMULATION PRODUCES A PREDICTION OF THE RECEIVED SIGNAL THROUGH
C  AN ACOUSTIC CHANNEL.  THE TRANSMITTED SIGNAL IS MFQPSK SIGNAL.
C
      REAL NU(100,1350), PHI(100,1350), U1, DELU1
      REAL FREQ, FF, ABSORP, AAUNDB, TL, AA(100,1350)
      REAL YRX, YY, TIME(410000), YYRX(410000)
      REAL RXKM(0:4096), RXKP(0:4096), RXKPD(0:4096), KFREQ(0:4096)
      REAL DELT(100), DELF(100)
      REAL VX(100), X(100)
      REAL VY(100), Y(100)
      REAL VZ(100), Z(100)
      REAL C(100), R(100), THETAD(100)
      REAL TAUL(100), ALPHA(100), ALPHAM(100), DELALF(100)
      REAL UHATI(100), LBAUD(100), PTOT(100), NOSVAR(100)
      REAL TAUK(1350), NOSAVG, NOISE

      INTEGER BDTYPE(100), BDTOTL, NBAUDS(50), IDFT
      INTEGER KMIN(100), KMAX(100), KX(100), M(100), KPTS(100)
      INTEGER IIPHI(100,1350), IPHI

      COMPLEX RXIN(0:4096), RXOUT(0:4096)

      DOUBLE PRECISION DSEED

      CHARACTER*40 PLABEL

C
C   USER INPUTS FOR THE SIMULATION
C
      WRITE(6,1000)
      READ(5,*) X0, Y0, Z0
C
      WRITE(30,1000)
      WRITE(30,*) ' X0 = ',X0,' Y0 = ',Y0,' Z0 = ',Z0
      WRITE(30,*) '  '
C
      WRITE(6,1001)
      READ(5,*) VXAVG, VXVAR, VYAVG, VYVAR, VZAVG, VZVAR
C
      WRITE(30,1001)
      WRITE(30,*) ' VXAVG = ',VXAVG,'  VXVAR = ',VXVAR
      WRITE(30,*) ' VYAVG = ',VYAVG,'  VYVAR = ',VYVAR
      WRITE(30,*) ' VZAVG = ',VZAVG,'  VZVAR = ',VZVAR
      WRITE(30,*) ' '
C
      WRITE(6,1002)
      READ(5,*) C0, CVAR
C
      WRITE(30,1002)
      WRITE(30,*) ' C0 = ',C0,' CVAR = ',CVAR
      WRITE(30,*) ' '
C
      WRITE(6,1003)
      READ(5,*) THETA0
C
      WRITE(30,1003)
      WRITE(30,*) ' THETA0 = ',THETA0
      WRITE(30,*) ' '
C
      WRITE(6,1004)
      READ(5,*) IAMP
C
C
      WRITE(30,1004)
      WRITE(30,*) ' IAMP = ',IAMP
      WRITE(30,*) ' '
C
C   INITIALIZE VARIABLES
C
C   BDTOTL = THE TOTAL NUMBER OF BAUDS IN THE SIGNAL
C   R0 = CLOSEST POINT OF APPROACH
C
```

```
      BDTOTL = 0
      R0 = 10**15.0
      X(1) = X0
      Y(1) = Y0
      Z(1) = Z0
C
      IF (X0 .GT. 0)  VXAVG = -ABS(VXAVG)
      IF (X0 .LE. 0)  VXAVG = ABS(VXAVG)
      IF (Y0 .GT. 0)  VYAVG = -ABS(VYAVG)
      IF (Y0 .LE. 0)  VYAVG = ABS(VYAVG)
      IF (Z0 .GT. 0)  VZAVG = -ABS(VZAVG)
      IF (Z0 .LE. 0)  VZAVG = ABS(VZAVG)
C
      WRITE(6,1010)
      READ(5,*) NPAKS
C
      WRITE(30,1010)
      WRITE(30,*) ' NPAKS = ',NPAKS
      WRITE(30,*) '  '
C
   10 WRITE(6,1100)
      WRITE(6,1101)
      WRITE(6,1102)
      WRITE(6,1103) NPAKS
      READ(5,*) METHOD
C
      WRITE(30,1100)
      WRITE(30,1101)
      WRITE(30,1102)
      WRITE(30,1103) NPAKS
      WRITE(30,*) ' METHOD = ',METHOD
      WRITE(30,*) '  '
C
      IF (METHOD .LE. 0) GO TO 10
      IF (METHOD .GE. 3) GO TO 10
      DO 100  I = 1, NPAKS
   50   WRITE(6,1020)
        WRITE(6,1021) I
        WRITE(6,1022)
        WRITE(6,1023)
        WRITE(6,1024)
        WRITE(6,1025)
        WRITE(6,1026)
        READ(5,*) BDTYPE(I)
C
        WRITE(30,1020)
        WRITE(30,1021) I
        WRITE(30,1022)
        WRITE(30,1023)
        WRITE(30,1024)
        WRITE(30,1025)
        WRITE(30,1026)
        WRITE(30,*) ' BDTYPE(',I,') = ',BDTYPE(I)
        WRITE(30,*) '  '
C
        IF (BDTYPE(I) .LE. 0) GO TO 50
        IF (BDTYPE(I) .GT. 5) GO TO 50
   60   WRITE(6,1027) I
        READ(5,*) NBAUDS(I)
C
        WRITE(30,1027) I
        WRITE(30,*) ' NBAUDS(',I,') = ',NBAUDS(I)
        WRITE(30,*) '  '
C
        IF (NBAUDS(I) .LE. 0) GO TO 60
  100 CONTINUE
      WRITE(6,1030)
      READ(5,*) IDFT
C
      WRITE(30,1030)
      WRITE(30,*) ' IDFT = ',IDFT
      WRITE(30,*) '  '
```

```
C
      IF (IDFT .EQ. 1)  THEN
        WRITE(6,1040)
        READ(5,*) IWNDOW
C
        WRITE(30,1040)
        WRITE(30,*) ' IWNDOW = ',IWNDOW
        WRITE(30,*) '  '
C
      ENDIF
      WRITE(6,1050)
      READ(5,*) SNRDB
C
      WRITE(30,1050)
      WRITE(30,'(A10,F10.4)') ' SNRDB = ',SNRDB
      WRITE(30,*) '  '
C
      SNRIN = 10.0**(SNRDB/10.0)
C
      LL = 0
      DO 300  I = 1, NPAKS
        DO 200  J = 1, NBAUDS(I)
          LL = LL + 1
          IF (BDTYPE(I) .EQ. 1)  THEN
            DELT(LL) = 1.0 / 240.0
            DELF(LL) = 240.0
            KMIN(LL) = 68
            KMAX(LL) = 83
            KX(LL) = 256
          ENDIF
          IF (BDTYPE(I) .EQ. 2)  THEN
            DELT(LL) = 1.0 / 120.0
            DELF(LL) = 120.0
            KMIN(LL) = 135
            KMAX(LL) = 166
            KX(LL) = 512
          ENDIF
          IF (BDTYPE(I) .EQ. 3)  THEN
            DELT(LL) = 1.0 / 60.0
            DELF(LL) = 60.0
            KMIN(LL) = 269
            KMAX(LL) = 332
            KX(LL) = 1024
          ENDIF
          IF (BDTYPE(I) .EQ. 4)  THEN
            DELT(LL) = 1.0 / 30.0
            DELF(LL) = 30.0
            KMIN(LL) = 537
            KMAX(LL) = 664
            KX(LL) = 2048
          ENDIF
          IF (BDTYPE(I) .EQ. 5)  THEN
            DELT(LL) = 1.0 / 15.0
            DELF(LL) = 15.0
            KMIN(LL) = 1073
            KMAX(LL) = 1328
            KX(LL) = 4096
          ENDIF
  200   CONTINUE
  300 CONTINUE
C
C   INITIALIZE VARIABLES
C
      PI = 4.0*ATAN(1.0)
      BDTOTL = LL
      IF (BDTOTL .GT. 100)  THEN
        WRITE(6,*)'  ***  ERROR:  TOTAL NUMBER OF BAUDS EXCEEDS 100  '
        WRITE(30,*)'  ***  ERROR:  TOTAL NUMBER OF BAUDS EXCEEDS 100  '
        GO TO 9999
      ENDIF
C
C   ALLOW THE USER TO ENCODE THE PHASES
```

```
C
      IF (METHOD .EQ. 2)  THEN
        LL = 0
        DO 490  I = 1, NPAKS
          WRITE(6,1110) I
          WRITE(6,1111) I, I
  410     READ(5,*) MTHDPK
C
          WRITE(30,1110) I
          WRITE(30,1111) I, I
          WRITE(30,*) ' MTHDPK = ',MTHDPK
          WRITE(30,*) '  '
C
          IF (MTHDPK .LE. 0)  GO TO 410
          IF (MTHDPK .GE. 3)  GO TO 410
          IF (MTHDPK .EQ. 1)  THEN
            DO 430  J = 1, NBAUDS(I)
              LL = LL + 1
              DO 420  K = KMIN(LL), KMAX(LL)
                DSEED = (K * 3.5729) + DSEED
                CALL PHASE(DSEED,RNDPHI,IPHI)
                PHI(LL,K) = RNDPHI
                IIPHI(LL,K) = IPHI
  420         CONTINUE
  430       CONTINUE
          ENDIF
          IF (MTHDPK .EQ. 2)  THEN
            DO 480  J = 1, NBAUDS(I)
              LL = LL + 1
              WRITE(6,1120) I, J
              WRITE(6,1121) I, J, I, J
  440         READ(5,*) MTHDBD
C
              WRITE(30,1120) I, J
              WRITE(30,1121) I, J, I, J
              WRITE(30,*) ' MTHDBD = ',MTHDBD
              WRITE(30,*) '  '
C
              IF (MTHDBD .LE. 0)  GO TO 440
              IF (MTHDBD .GE. 3)  GO TO 440
              IF (MTHDBD .EQ. 1)  THEN
                DO 450  K = KMIN(LL), KMAX(LL)
                  DSEED = (K * 5.7317) + DSEED
                  CALL PHASE(DSEED,RNDPHI,IPHI)
                  PHI(LL,K) = RNDPHI
                  IIPHI(LL,K) = IPHI
  450           CONTINUE
              ENDIF
              IF (MTHDBD .EQ. 2)  THEN
                WRITE(6,1100)
                WRITE(6,1101)
C
                WRITE(30,1100)
                WRITE(30,1101)
C
                DO 470  K = KMIN(LL), KMAX(LL)
  460             WRITE(6,1130) I, J, K
                  READ(5,*) IPHI
                  IIPHI(LL,K) = IPHI
C
                  WRITE(30,1130) I, J, K
                  WRITE(30,*) ' IPHI = ',IPHI
                  WRITE(30,*) '  '
C
                  IF (IPHI .LE. 0)  GO TO 460
                  IF (IPHI .GE. 5)  GO TO 460
                  IF (IPHI .EQ. 1) PHI(LL,K) = (45.0 * PI) / 180.0
                  IF (IPHI .EQ. 2) PHI(LL,K) = (135.0 * PI) / 180.0
                  IF (IPHI .EQ. 3) PHI(LL,K) = (-135.0 * PI) / 180.0
                  IF (IPHI .EQ. 4) PHI(LL,K) = (-45.0 * PI) / 180.0
  470           CONTINUE
              ENDIF
```

```
  480        CONTINUE
           ENDIF
  490    CONTINUE
         ENDIF
C
         DO 550  LL = 1, BDTOTL
C
C    INITIALIZE VARIABLES
C
           DSEED = (LL * 15.5987) + DSEED
           LBAUD(LL) = LL
C
C    COMPUTE:
C                X(LL) = DISTANCE THE TRANSMITTER TRAVELED IN THE
C                        X-DIRECTION DURING THE LLTH BAUD
C
           CALL GAUSS(DSEED,VXAVG,VXVAR,ZRND)
           VX(LL) = ZRND
           IF (LL .GT. 1) X(LL) = X(LL-1) + (VX(LL) * DELT(LL))
C
C
C    COMPUTE:
C                Y(LL) = DISTANCE THE TRANSMITTER TRAVELED IN THE
C                        Y-DIRECTION DURING THE LLTH BAUD
C
           CALL GAUSS(DSEED,VYAVG,VYVAR,ZRND)
           VY(LL) = ZRND
           IF (LL .GT. 1) Y(LL) = Y(LL-1) + (VY(LL) * DELT(LL))
C
C
C    COMPUTE:
C                Z(LL) = DISTANCE THE TRANSMITTER TRAVELED IN THE
C                        Z-DIRECTION DURING THE LLTH BAUD
C
           CALL GAUSS(DSEED,VZAVG,VZVAR,ZRND)
           VZ(LL) = ZRND
           IF (LL .GT. 1) Z(LL) = Z(LL-I) + (VZ(LL) * DELT(LL))
C
C
C    COMPUTE:
C                C(LL) = THE SPEED OF SOUND DURING THE LTH BAUD
C
           CALL GAUSS(DSEED,C0,CVAR,ZRND)
           C(LL) = ZRND
C
C    COMPUTE:
C                R(LL) = SLANT RANGE TO THE RECEIVER
C
           XXX = ABS(X(LL))
           YYY = ABS(Y(LL))
           ZZZ = ABS(Z(LL))
           R(LL) = ( XXX**2.0 + YYY**2.0 + ZZZ**2.0 )**0.5
           IF (R(LL) .LE. R0)  R0 = R(LL)
C
C    COMPUTE:
C                THETAD(LL) = ANGLE BETWEEN THE SLANT RANGE AND Z0
C
           ARG = ABS(Z(LL)) / R(LL)
           THETAD(LL) = ACOS(ARG) * (180.0/PI)
           IF (THETAD(LL) .GT. THETA0)  THEN
             WRITE(6,*)
      %      ' ** WARNING:  THETA IS GREATER THAN ',THETA0,' DEGREES ** '
             WRITE(6,*)
      %      ' ***********  THE RECEIVER CAN NOT RECEIVE THE SIGNAL   ** '
             WRITE(6,*)'   '
             WRITE(30,*)
      %      ' ** WARNING:  THETA IS GREATER THAN ',THETA0,' DEGREES ** '
             WRITE(30,*)
      %      ' ***********  THE RECEIVER CAN NOT RECEIVE THE SIGNAL   ** '
             WRITE(30,*)'   '                                   ,
           ENDIF
C
```

```
C     INITIALIZE LIMITS FOR GRAPHS
C
         IF (LL .EQ. 1)  THEN
           XXMIN = INT(X(I))
           XXMAX = INT(X(1)) + 1.0
           YYMIN = INT(Y(1))
           YYMAX = INT(Y(1)) + I.0
           ZZMIN = INT(Z(1))
           ZZMAX = INT(Z(I)) + I.0
           CCMIN = INT(C(1))
           CCMAX = INT(C(1)) + 1.0
           RRMIN = INT(R(I))
           RRMAX = INT(R(1)) + 1.0
           THTMIN = INT(THETAD(1))
           THTMAX = INT(THETAD(1)) + 0.5
         ENDIF
C
C     SET LIMITS FOR GRAPHS
C
         IF (X(LL) .LT. XXMIN) XXMIN = X(LL)
         IF (X(LL) .GT. XXMAX) XXMAX = X(LL)
         IF (Y(LL) .LT. YYMIN) YYMIN = Y(LL)
         IF (Y(LL) .GT. YYMAX) YYMAX = Y(LL)
         IF (Z(LL) .LT. ZZMIN) ZZMIN = Z(LL)
         IF (Z(LL) .GT. ZZMAX) ZZMAX = Z(LL)
         IF (C(LL) .LT. CCMIN) CCMIN = C(LL)
         IF (C(LL) .GT. CCMAX) CCMAX = C(LL)
         IF (R(LL) .LT. RRMIN) RRMIN = R(LL)
         IF (R(LL) .GT. RRMAX) RRMAX = R(LL)
         IF (THETAD(LL) .LT. THTMIN) THTMIN = THETAD(LL)
         IF (THETAD(LL) .GT. THTMAX) THTMAX = THETAD(LL)
C
C    ASSIGN ALL THE PHASES RANDOMLY FOR EVERY PACKET
C
         DO 500  K = KMIN(LL), KMAX(LL)
           IF (METHOD .EQ. 1)  THEN
             DSEED = (K * 2.767653) + DSEED
             CALL PHASE(DSEED,RNDPHI,IPHI)
             PHI(LL,K) = RNDPHI
             IIPHI(LL,K) = IPHI
           ENDIF
C
  500    CONTINUE
  550 CONTINUE
C
       DO 660  LL = 1, BDTOTL
C
C    COMPUTE:
C            ALPHA(LL) = THE DOPPLER COMPRESSION FACTOR
C                        DUE TO THE MOVING TRANSMITTER
C
         AVX = VXAVG * X(LL)
         AVY = VYAVG * Y(LL)
         AVZ = VZAVG * Z(LL)
         ALPHA(LL) = (AVX + AVY + AVZ) / (R(LL)*C(LL))
C
C    COMPUTE:
C            DELALF(LL) = THE MAXIMUM CHANGE IN ALPHA FOR THE LTH BAUD
C            M(LL) = THE DOPPLER CHANNEL # NEEDED FOR THE LTH BAUD
C            ALPHAM(LL) = THE DOPPLER CHANNEL FACTOR FOR THE LTH BAUD
C                         NOTE:
C                           ALPHAM(LL) IS USED TO ESTIMATE THE SAMPLING
C                           FREQUENCY OF THE RECEIVED SIGNAL
C
         DELALF(LL) = 1 / (8.0 * KMAX(LL))
         AMIN = (ALPHA(LL) / DELALF(LL)) - 0.5
         AMAX = (ALPHA(LL) / DELALF(LL)) + 0.5
         M(LL) = INT((AMIN + AMAX) / 2.0)
         ALPHAM(LL) = M(LL) * DELALF(LL)
C
C    COMPUTE:
C            TAUL(LL) = THE TIME DELAY DUE TO THE SIGNAL TRAVELING
```

```
C                      THROUGH THE MEDIUM OR CHANNEL AND THE RECEIVER
C                      FOR THE LTH BAUD
C
         TAUL(LL) = R(LL) / C(LL)
C
         IF (LL .EQ. 1)  THEN
           ALFMIN = INT(ALPHA(1))
           ALFMAX = INT(ALPHA(1)) + 0.1
         ENDIF
         IF (ALPHA(LL) .LT. ALFMIN) ALFMIN = ALPHA(LL)
         IF (ALPHA(LL) .GT. ALFMAX) ALFMAX = ALPHA(LL)
         PTOT(LL) = 0.0
         NOSVAR(LL) = 0.0
         DO 640  K = KMIN(LL), KMAX(LL)
C
C   COMPUTE:
C           U1 = THE RECEIVE SIGNAL SAMPLE START TIME
C           DELU1 = THE SYNCHRONIZATION ERROR
C
C          WRITE(6,1140) LL, K
C1140 FORMAT(/,2X,'ENTER THE ESTIMATED RECEIVE SIGNAL START TIME ',/,2X,
C    % '  FOR BAUD NUMBER ',I4,/,4X,
C    % '  AND THE TIME DELAY THROUGH THE TRANSMITTER ',/,4X,
C    % '    ELECTRONICS FOR TONE NUMBER ',I4,' ... ')
C          READ(5,*)  UHAT1(LL), TAUK(K)
           TAUK(K) = 0.005
           U1 = TAUL(LL) + (TAUK(K) * (1 + ALPHA(LL)))
           UHAT1(LL) = U1
           DELU1 = U1 - UHAT1(LL)
C
C   COMPUTE:
C           NU(LL,K) = A RANDOM SEQUENCE OF TIMING JITTERS
C
           NU(LL,K) = (DELU1/DELT(LL)) * (KX(LL)/(1+ALPHAM(LL)))
C
C   COMPUTE:
C           AA(LL,K) = THE AMPLITUDE OF THE RECEIVED SIGNAL, WHICH IS
C                      1 FOR ALL LL AND K IF NORMALIZED AMPLITUDES ARE
C                      DESIRED (I.E., IAMP=1), OR ATTENUATION FACTOR
C                      DUE TO THE TRANSMISSION LOSS IF NORMALIZED
C                      AMPLITUDES ARE NOT DESIRED (I.E., IAMP=0)
C
           IF (IAMP .EQ. 0) THEN
C
C   COMPUTE:
C           ABSORP = THE AMOUNT OF ABSORPTION IN DB/FT AT 4 DEGREES C
C                    AT A DEPTH OF APPROXIMATELY 3000 FT
C
             FREQ = (K * DELF(LL)) / 1000.0
             FF = FREQ**2.0
             ABSORP = (0.003 + ( (0.1*FF) / (1+FF) )
     %                       + ( (40.0*FF) / (4.100+FF) )
     %                       + ( 0.000275 * FF )) / 3000
C
C     TXDEP = THE DEPTH THE TRANSMITTER IS BELOW THE SURFACE IN FEET
C
             TXDEP = 1000.0
             ZTOTAL = TXDEP + ABS(Z(LL))
C
             AAUNDB = 10 ** (ABSORP / 20.0)
             IFAC = INT((ZTOTAL - 3000.0) / 1000.0)
             IF (IFAC .LT. 0) FACTOR = 1.02
             IF (IFAC .GT. 0) FACTOR = 0.98
             IIFAC = ABS(IFAC)
             IF (IIFAC .NE. 0)  THEN
               DO 620  I = 1, IIFAC
                 AAUNDB = AAUNDB * FACTOR
  620          CONTINUE
             ENDIF
             ABSORP = 20.0 * ALOG10(AAUNDB)
C
C   COMPUTE:
```

```
C            TL = THE TRANSMISSION LOSS IN DB DUE TO SPHERICAL-SPREADING
C                 AND ABSORPTION OF THE ACOUSTIC CHANNEL
C
             TL = (20.0 * ALOG10(ZTOTAL)) + (ABSORP * ZTOTAL)
C
             AA(LL,K) = 10.0**(-(TL/20.0))
           ELSE
             AA(LL,K) = 1.0
           ENDIF
C
C    COMPUTE THE NOISE VARIANCE FOR THE DESIRED
C      WIDE BAND SIGNAL-TO-NOISE RATIO
C
C         PTOT(LL) = THE TOTAL POWER OF THE LLTH BAUD
C         NOSVAR(LL) = THE NOISE VARIANCE OF THE LLTH BAUD
C
           PTOT(LL) = PTOT(LL) + ( (AA(LL,K)**2)/2.0 )
  640    CONTINUE
         KPTS(LL) = (KMAX(LL) - KMIN(LL)) + 1
         NOSVAR(LL) = (PTOT(LL) * KX(LL)) / (2.0 * SNRIN * KPTS(LL))
  660 CONTINUE
C
      II = 0
      RXMAX = 0.0
      RXMIN = 0.0
      NOSAVG = 0.0
      NOISE = 0.0
      DO 700  LL = 1, BDTOTL
        DO 690  N = 1, KX(LL)
          DSEED = (LL * 32.7673) + DSEED
          CALL GAUSS(DSEED,NOSAVG,NOSVAR(LL),NOISE)
          YRX = 0.0
          NN = N - 1
          II = II + 1
          TIME(II) = II - 1
          DO 680  K = KMIN(LL), KMAX(LL)
C
C
C    COMPUTE:
C            YRX = THE RECEIVED SIGNAL WITH ALL OF THE ABOVE
C                  PARAMETERS COMBINED FOR THE LTH BAUD
C                  AT TIME = NN OVER ALL KMIN TO KMAX FREQUENCIES
C
            YY = AA(LL,K) * COS( (((2*PI*K)/KX(LL)) *
     %            ((1+ALPHAM(LL)) / (1+ALPHA(LL))) *
     %            (NN - NU(LL,K))) + PHI(LL,K) )
            YRX = YRX + YY
  680     CONTINUE
          YYRX(II) = YRX + NOISE
          IF (YYRX(II) .GT. RXMAX) RXMAX = YYRX(II)
          IF (YYRX(II) .LT. RXMIN) RXMIN = YYRX(II)
  690   CONTINUE
  700 CONTINUE
C
      NPTS = II
      KLL = 0
      DO 710  LL = 1, BDTOTL
        KLL = KLL + KPTS(LL)
  710 CONTINUE
      WRITE(30,2000) KLL
      WRITE(30,2001)'      LL        K     PHI(LL,K)    IPHI '
      DO 740  LL = 1, BDTOTL
        DO 720  K = KMIN(LL), KMAX(LL)
          WRITE(30,2010) LL, K, PHI(LL,K), IIPHI(LL,K)
  720   CONTINUE
  740 CONTINUE
C
C   COMPUTE THE DFT OF THE OUTPUT (RECEIVED) SIGNAL
C
      IF (IDFT .EQ. 1)  THEN
        RXKMIN = 0.0
        RXKMAX = 0.0
```

```
         DO 800  LL = I, BDTOTL
           II = 0
           IF (LL .EQ. I)  THEN
             JJ = I
           ELSE
             JJ = JJJ + 1
           ENDIF
           KXMI = KX(LL) - I
           JJJ = JJ + KXM1
           DO 760  J = JJ, JJJ
             RXIN(II) = CMPLX(YYRX(J),0.0)
             II = II + I
  760      CONTINUE
           CALL DFT(KXMI,RXIN,RXOUT)
C
C  CONVERT OUTPUT DATA TO EXPONENTIAL FORM,  I.E., RXKM()*EXP(J*RXKP())
C
           DO 770  I = 0, KXMI
             RXKM(I) = SQRT( (REAL(RXOUT(I)))**2 + (AIMAG(RXOUT(I)))**2 )
             IF (ABS(REAL(RXOUT(I))) .GE. I.E-I5)  THEN
               RXKP(I) = ATAN2(AIMAG(RXOUT(I)), REAL(RXOUT(I)))
             ELSE
               IF (ABS(AIMAG(RXOUT(I))) .LE. I.E-I5)  RXKP(I) = 0.0
               IF (AIMAG(RXOUT(I)) .GT. I.E-I5)  RXKP(I) = PI/2.0
               IF (AIMAG(RXOUT(I)) .LT. -1.E-I5)  RXKP(I) = -PI/2.0
             ENDIF
             RXKPD(1) = (RXKP(I) * 180.0) / PI
  770      CONTINUE
C
C   WRITE DFT INPUT AND OUTPUT TO A FILE
C
           WRITE(30,2200) LL
           DO 780  I = 0, KXM1
             WRITE(30,2210) I, REAL(RXIN(I)), AIMAG(RXIN(I))
  780      CONTINUE
           WRITE(30,2220) LL
           IF (IWNDOW .EQ. 0)  THEN
             IMIN = 0
             IMAX = KXM1
             WMIN = 0
             WMAX = KXM1
           ELSE
             IMIN = KMIN(LL)
             IMAX = KMAX(LL)
             WMIN = KMIN(LL)
             WMAX = KMAX(LL)
           ENDIF
           KXX = (IMAX - IMIN) + 1
           DO 790  I = IMIN, IMAX
             WRITE(30,2230) I, REAL(RXOUT(I)), AIMAG(RXOUT(I)),
     %                         RXKM(I), RXKPD(I), RXKP(I)
             IF (RXKM(I) .LT. RXKMIN) RXKMIN = RXKM(I)
             IF (RXKM(I) .GT. RXKMAX) RXKMAX = RXKM(I)
             KFREQ(I) = I
  790      CONTINUE
C
C   PLOT THE DFT OUTPUT
C
           WRITE(PLABEL,2300) LL
           IF (LL .EQ. 1) CALL COMPRS
           CALL PAGE(11,8.5)
           CALL NOBRDR
           CALL AREA2D(8,6)
           CALL XNAME('  FREQ (K) $',100)
           CALL YNAME('  MAGNITUDE $',100)
           CALL HEADIN(' DFT OUTPUT OF THE RECEIVED SIGNAL $',I00,4,2)
           CALL HEADIN(PLABEL,I00,3,2)
           CALL GRAF(WMIN,'SCALE',WMAX,RXKMIN,'SCALE',RXKMAX)
           CALL GRID(I,I)
           CALL SETCLR('MAGENTA')
           IF (KXX .LE. 100)  THEN
             CALL CURVE(KFREQ(IMIN),RXKM(IMIN),KXX,-I)
```

```
          CALL VLINE(IMIN,IMAX,KFREQ,RXKM)
        ELSE
          CALL CURVE(KFREQ(IMIN),RXKM(IMIN),KXX,0)
        ENDIF
        CALL ENDGR(0)
        CALL ENDPL(0)
C
        CALL PAGE(11,8.5)
        CALL NOBRDR
        CALL AREA2D(8,6)
        CALL XNAME('  FREQ (K) $',100)
        CALL YNAME('  PHASE (DEG) $',100)
        CALL HEADIN(' DFT OUTPUT OF THE RECEIVED SIGNAL $',100,4,2)
        CALL HEADIN(PLABEL,100,3,2)
        CALL GRAF(WMIN,'SCALE',WMAX,-180.0,45.0,180.0)
        CALL GRID(1,1)
        CALL SETCLR('MAGENTA')
        IF (KXX .LE. 100)  THEN
          CALL CURVE(KFREQ(IMIN),RXKPD(IMIN),KXX,-1)
          CALL VLINE(IMIN,IMAX,KFREQ,RXKPD)
        ELSE
          CALL CURVE(KFREQ(IMIN),RXKPD(IMIN),KXX,0)
        ENDIF
        CALL ENDGR(0)
        CALL ENDPL(0)
  800   CONTINUE
      ENDIF

C
C   FORMATS
C
 1000 FORMAT(/,2X,
     % 'PLEASE ENTER THE INITIAL POSITION  X0,Y0,Z0 (FT) ',/,2X,
     % '  OF THE RECEIVER RELATIVE TO THE TRANSMITTER ...')
 1001 FORMAT(/,2X,
     % 'ENTER THE TRANSMITTER"S VELOCITY AVERAGE AND VARIANCE',/,2X,
     % '  IN THE X, Y, Z-DIRECTIONS (FT/SEC) AND (FT/SEC)**2  ...',/,2X,
     % '  (I.E.  VXAVG, VXVAR, VYAVG, VYVAR, VZAVG, VZVAR) ')
 1002 FORMAT(/,2X,
     % 'ENTER THE AVERAGE SPEED OF SOUND IN FT/SEC ',/,2X,
     % '  AND THE VARIANCE IN (FT/SEC)**2  ...')
 1003 FORMAT(/,2X,
     % 'ENTER THE TRANSMITTER"S DOWN LINK TRANSMITTED ',/,2X,
     % '  HALF BEAM WIDTH ANGLE (DEG)  ...')
 1004 FORMAT(/,2X,'DO YOU WANT NORMALIZED AMPLITUDE ',
     % 'FOR THE RECEIVED SIGNAL?',/,2X,
     %  '       PLEASE ENTER 1:YES OR 0:NO ...')
 1010 FORMAT(2X,'ENTER THE # OF PACKETS IN THE TRANSMITTED SIGNAL ...')
 1020 FORMAT(/,2X,
     % 'ENTER THE BAUD TYPE # CORRESPONDING TO THE FOLLOWING ')
 1021 FORMAT(2X,'  BAUD LENGTH FOR PACKET NUMBER: ',I4,' ...')
 1022 FORMAT(/,10X,' 1 : BAUD LENGTH (DELT) = 1/240 SECONDS ')
 1023 FORMAT(10X,' 2 : BAUD LENGTH (DELT) = 1/120 SECONDS ')
 1024 FORMAT(10X,' 3 : BAUD LENGTH (DELT) = 1/60 SECONDS ')
 1025 FORMAT(10X,' 4 : BAUD LENGTH (DELT) = 1/30 SECONDS ')
 1026 FORMAT(10X,' 5 : BAUD LENGTH (DELT) = 1/15 SECONDS ')
 1027 FORMAT(/,2X,
     %  'ENTER THE NUMBER OF BAUDS IN PACKET NUMBER: ',I4,' ...')
 1030 FORMAT(//,2X,'WOULD YOU LIKE THE DISCETE FOURIER TRANSFORM ',/,
     %  2X,'  OF THE OUTPUT SIGNAL ?  (ENTER  1:YES OR 0:NO) ... ')
 1040 FORMAT(/,2X,
     % 'WOULD YOU LIKE THE DFT OUTPUT WINDOWED ? ',/,2X,
     % '  ENTER  1:YES OR 0:NO ... ')
 1050 FORMAT(/,2X,
     % 'PLEASE ENTER THE DESIRED INPUT WIDE BAND ',/,2X,
     % '    SIGNAL-TO-NOISE RATIO IN DB ... ')
 1100 FORMAT(/,2X,
     % 'THIS PROGRAM ENCODES A QPSK MULTIFREQUENCY SIGNAL.',/,2X,
     % '  THE PHASES ARE SHOWN BELOW FOR ONE FREQUENCY ...')
 1101 FORMAT(//,
     % 6X,'                 ',' ','                    ',/,
     % 6X,'      *          ',' ','         *          ',/,
```

```
     % 6X,'      2           ',' ',' '          1        ',/,
     % 6X,'                  ',' ',' '                   ',/,
     % 6X,'                  ',' ',' '                   ',/,
     % 6X,'                  ',' ',' '                   ',/,
     % 6X,'__________________',' ',' '__________________',/,
     % 6X,'                  ',' ',' '                   ',/,
     % 6X,'                  ',' ',' '                   ',/,
     % 6X,'                  ',' ',' '                   ',/,
     % 6X,'      *           ',' ',' '          *        ',/,
     % 6X,'      3           ',' ',' '          4        ',/,
     % 6X,'                  ',' ',' '                   ',///)
 1102 FORMAT(//,2X,
     % 'SELECT ONE OF THE FOLLOWING METHODS FOR ENCODING ',/,4X,
     % 'THE PHASES FOR EACH FREQUENCY FOR EVERY BAUD ',/,4X,
     % 'WITHIN EACH PACKET ...')
 1103 FORMAT(/,5X,'ENTER ...',/,7X,
     % '1: THE PROGRAM RANDOMLY SELECTS ALL THE PHASES ',/,7X,
     % '     FOR ALL ',I4,' PACKETS ',/,7X,
     % '2: YOU INDIVIDUALLY SELECT THE PHASES ')
 1110 FORMAT(//,2X,
     % 'SELECT ONE OF THE FOLLOWING METHODS FOR ENCODING ',/,4X,
     % 'THE PHASES FOR PACKET NUMBER: ',I4,' ...')
 1111 FORMAT(/,5X,'ENTER ...',/,7X,
     % '1: THE PROGRAM RANDOMLY SELECTS ALL THE PHASES ',/,7X,
     % '     FOR PACKET NUMBER: ',I4,/,7X,
     % '2: YOU INDIVIDUALLY SELECT THE PHASES ',/,7X,
     % '     FOR PACKET NUMBER: ',I4)
 1120 FORMAT(//,2X,
     % 'SELECT ONE OF THE FOLLOWING METHODS FOR ENCODING ',/,4X,
     % 'THE PHASES FOR PACKET NUMBER: ',I4,' BAUD NUMBER: ',I4,' ...')
 1121 FORMAT(/,5X,'ENTER ...',/,7X,
     % '1: THE PROGRAM RANDOMLY SELECTS ALL THE PHASES ',/,7X,
     % '     FOR PACKET NUMBER: ',I4,' BAUD NUMBER: ',I4,/,7X,
     % '2: YOU INDIVIDUALLY SELECT THE PHASES ',/,7X,
     % '     FOR PACKET NUMBER: ',I4,' BAUD NUMBER: ',I4)
 1130 FORMAT(//,2X,
     % 'PLEASE ENTER THE DESIRED QUADRANT FOR THE PHASE ',/,4X,
     % 'OF PACKET NUMBER: ',I4,' BAUD NUMBER: ',I4,/,4X,
     % 'FREQUENCY NUMBER (K): ',I4,' ...')
C
 2000 FORMAT(I8)
 2001 FORMAT(A38)
 2010 FORMAT(2X,I6,2X,I6,2X,F10.3,2X,I4)
 2020 FORMAT(//,2X,I8)
 2100 FORMAT(2X,I6,4X,F14.4)
 2200 FORMAT(//,2X,' DFT INPUT DATA FOR BAUD # ',I4,/,5X,
     % 'N',5X,'REAL PART',5X,'IMAG PART')
 2210 FORMAT(2X,I4,2X,E12.6,2X,E12.6)
 2220 FORMAT(//,2X,' DFT OUTPUT DATA FOR BAUD # ',I4,/,5X,
     %'K',7X,'REAL PART',7X,'IMAG PART',7X,'MAGNITUDE',16X,'PHASE',/,
     % 64X,'(DEG)',11X,'(RAD)')
 2230 FORMAT(2X,I4,2X,E14.8,2X,E14.8,2X,E14.8,4X,E14.8,2X,E14.8)
 2300 FORMAT(' FOR BAUD NUMBER ',I4,' $')
C
C   PLOTTING
C
             XXMIN = INT(XXMIN) - 0.2
             XXMAX = INT(XXMAX) + 0.2
             YYMIN = INT(YYMIN) - 0.2
             YYMAX = INT(YYMAX) + 0.2
             ZZMIN = INT(ZZMIN) - 0.2
             ZZMAX = INT(ZZMAX) + 0.2
             CCMIN = INT(CCMIN) - 1.0
             CCMAX = INT(CCMAX) + 1.0
             RRMIN = INT(RRMIN) - 1.0
             RRMAX = INT(RRMAX) + 1.0
             ALFMIN = INT(ALFMIN) - 0.2
             ALFMAX = INT(ALFMAX) + 0.2
             THTMIN = INT(THTMIN) - 0.4
             THTMAX = INT(THTMAX) + 0.4
C
      IF (IDFT .EQ. 0)  CALL COMPRS
```

```
      CALL PAGE(11,8.5)
      CALL NOBRDR
      CALL AREA2D(8,6)
      CALL XNAME('  TIME (N) $',100)
      CALL YNAME('  MAGNITUDE $',100)
      CALL HEADIN(' RECEIVED SIGNAL $',100,3,1)
      CALL GRAF(0,'SCALE',NPTS,RXMIN,'SCALE',RXMAX)
      CALL GRID(1,1)
      CALL SETCLR('GREEN')
      CALL CURVE(TIME,YYRX,NPTS,0)
      CALL ENDGR(0)
      CALL ENDPL(0)
      IF (BDTOTL .GT. 1)  THEN
        CALL PAGE(11,8.5)
        CALL NOBRDR
        CALL AREA2D(8,6)
        CALL XNAME('  BAUD (LL) $',100)
        XXM = XXMAX - XXMIN
        IF (XXM .GE. 100.0)  THEN
          XXMIN = XXMIN / 1000.0
          XXMAX = XXMAX / 1000.0
          CALL YNAME('  X(LL) (KFT)     $',100)
          DO 900  I = 1, BDTOTL
            X(I) = X(I) / 1000.0
900       CONTINUE
        ELSE
          CALL YNAME('  X(LL) (FT)     $',100)
        ENDIF
        CALL HEADIN(' X-POSITION       $',100,3,1)
        CALL GRAF(1,'SCALE',BDTOTL,XXMIN,'SCALE',XXMAX)
        CALL GRID(1,1)
        CALL SETCLR('CYAN')
        CALL CURVE(LBAUD,X,BDTOTL,0)
        CALL ENDGR(0)
        CALL ENDPL(0)
        CALL PAGE(11,8.5)
        CALL NOBRDR
        CALL AREA2D(8,6)
        CALL XNAME('  BAUD (LL) $',100)
        YYM = YYMAX - YYMIN
        IF (YYM .GE. 100.0)  THEN
          YYMIN = YYMIN / 1000.0
          YYMAX = YYMAX / 1000.0
          CALL YNAME('  Y(LL) (KFT)     $',100)
          DO 905  I = 1, BDTOTL
            Y(I) = Y(I) / 1000.0
905       CONTINUE
        ELSE
          CALL YNAME('  Y(LL) (FT)     $',100)
        ENDIF
        CALL HEADIN(' Y-POSITION       $',100,3,1)
        CALL GRAF(1,'SCALE',BDTOTL,YYMIN,'SCALE',YYMAX)
        CALL GRID(1,1)
        CALL SETCLR('MAGENTA')
        CALL CURVE(LBAUD,Y,BDTOTL,0)
        CALL ENDGR(0)
        CALL ENDPL(0)
        CALL PAGE(11,8.5)
        CALL NOBRDR
        CALL AREA2D(8,6)
        CALL XNAME('  BAUD (LL) $',100)
        ZZM = ZZMAX - ZZMIN
        IF (ZZM .GE. 100.0)  THEN
          ZZMIN = ZZMIN / 1000.0
          ZZMAX = ZZMAX / 1000.0
          CALL YNAME('  Z(LL) (KFT)     $',100)
          DO 910  I = 1, BDTOTL
            Z(I) = Z(I) / 1000.0
910       CONTINUE
        ELSE
          CALL YNAME('  Z(LL) (FT)     $',100)
        ENDIF
```

```
      CALL HEADIN(' Z-POSITION       $',100,3,1)
      CALL GRAF(1,'SCALE',BDTOTL,ZZMIN,'SCALE',ZZMAX)
      CALL GRID(1,1)
      CALL SETCLR('BLUE')
      CALL CURVE(LBAUD,Z,BDTOTL,0)
      CALL ENDGR(0)
      CALL ENDPL(0)
      CALL PAGE(11,8.5)
      CALL NOBRDR
      CALL AREA2D(8,6)
      CALL XNAME('  BAUD (LL) $',100)
      CCM = CCMAX - CCMIN
      IF (CCMAX .GE. 100.0)  THEN
        CCMIN = CCMIN / 1000.0
        CCMAX = CCMAX / 1000.0
        CALL YNAME('  C(LL) (KFT/SEC)     $',100)
        DO 915  I = 1, BDTOTL
          C(I) = C(I) / 1000.0
915     CONTINUE
      ELSE
        CALL YNAME('  C(LL) (FT/SEC)     $',100)
      ENDIF
      CALL HEADIN(''SPEED OF SOUND  $',100,3,1)
      CALL GRAF(1,'SCALE',BDTOTL,CCMIN,'SCALE',CCMAX)
      CALL GRID(1,1)
      CALL SETCLR('RED')
      CALL CURVE(LBAUD,C,BDTOTL,0)
      CALL ENDGR(0)
      CALL ENDPL(0)
      CALL PAGE(11,8.5)
      CALL NOBRDR
      CALL AREA2D(8,6)
      CALL XNAME('  BAUD (LL) $',100)
      RRM = RRMAX - RRMIN
      IF (RRM .GE. 100.0)  THEN
        RRMIN = RRMIN / 1000.0
        RRMAX = RRMAX / 1000.0
        CALL YNAME('  R(LL) (KFT)     $',100)
        DO 920  I = 1, BDTOTL
          R(I) = R(I) / 1000.0
920     CONTINUE
      ELSE
        CALL YNAME('  R(LL) (FT)     $',100)
      ENDIF
      CALL HEADIN(' SLANT RANGE TO RECEIVER $',100,3,1)
      CALL GRAF(1,'SCALE',BDTOTL,RRMIN,'SCALE',RRMAX)
      CALL GRID(1,1)
      CALL SETCLR('GREEN')
      CALL CURVE(LBAUD,R,BDTOTL,0)
      CALL ENDGR(0)
      CALL ENDPL(0)
      CALL PAGE(11,8.5)
      CALL NOBRDR
      CALL AREA2D(8,6)
      CALL XNAME('  BAUD (LL) $',100)
      CALL YNAME('  ALPHA(LL)  $',100)
      CALL HEADIN('COMPRESSION FACTOR DUE TO THE MOVING TX $',100,3,1)
      CALL GRAF(1,'SCALE',BDTOTL,ALFMIN,'SCALE',ALFMAX)
      CALL GRID(1,1)
      CALL SETCLR('RED')
      CALL CURVE(LBAUD,ALPHA,BDTOTL,0)
      CALL ENDGR(0)
      CALL ENDPL(0)
      CALL PAGE(11,8.5)
      CALL NOBRDR
      CALL AREA2D(8,6)
      CALL XNAME('  BAUD (LL) $',100)
      CALL YNAME('  THETA(LL) (DEG) $',100)
      CALL HEADIN('ANGLE BETWEEN R(LL) AND ZO $',100,3,1)
      CALL GRAF(1,'SCALE',BDTOTL,THTMIN,'SCALE',THTMAX)
      CALL GRID(1,1)
      CALL SETCLR('BLUE')
```

```
        CALL CURVE(LBAUD,THETAD,BDTOTL,0)
        CALL ENDGR(0)
        CALL ENDPL(0)
      ENDIF
      CALL DONEPL

 9999 STOP
      END
C
      SUBROUTINE GAUSS(DSEED,AVG,VAR,ZRND)
C
C    THIS SUBROUTINE GENERATES A GAUSSIAN RANDOM NUMBER WITH
C    MEAN = AVG AND VARIANCE = VAR
C
C       INPUTS:  DSEED = A DOUBLE PRECISION SEED THAT MUST BE A VARIABLE
C                AVG   = THE MEAN OF THE GAUSSIAN RANDOM VARIABLE
C                VAR   = THE VARIANCE OF THE GAUSSIAN RANDOM VARIABLE
C
C       OUTPUTS:  DSEED = THE SEED IS CHANGED DURING EXECUTION WHICH IS
C                         REQUIRED FOR THE NEXT SUBROUTINE CALL
C                 ZRND  = A GAUSSIAN RANDOM NUMBER WITH MEAN = AVG AND
C                         VARIANCE = VAR
C
      REAL AVG, VAR, ZRND
      DOUBLE PRECISION ZZ, DSEED, URND
      ZZ = 0.0
      DO 3000  I = 1, 12
        DSEED = DSEED + 13579345.1397537
        URND = GGUBFS(DSEED)
        ZZ = (URND - 0.5) + ZZ
 3000 CONTINUE
      ZRND = (ZZ * (VAR**0.5)) + AVG
      RETURN
      END
C
      SUBROUTINE PHASE(DSEED,RNDPHI,IPHI)
C
C    THIS SUBROUTINE SELECTS A PHASE RANDOMLY FROM QUADRANTS 1 TO 4
C
C       INPUTS:   DSEED = A DOUBLE PRECISION SEED THAT MUST BE A VARIABLE
C
C       OUTPUTS:  DSEED = THE SEED IS CHANGED DURING EXECUTION WHICH IS
C                         REQUIRED FOR THE NEXT SUBROUTINE CALL
C                 RNDPHI = A RANDOM PHASE FROM ONE OF THE FOUR QUADRANTS
C                          IN RADIANS
C                 IPHI = THE QUADRANT NUMBER OF THE RANDOM PHASE
C
      REAL PHIRND, RNDPHI
      DOUBLE PRECISION DSEED
      INTEGER IPHI
C
      PI = 4.0*ATAN(1.0)
      PHIRND = 0.0
      IPHI = 0
      PHIRND = GGUBFS(DSEED)
      DSEED = DSEED + 127.453
      PHIRND = (PHIRND * 4.0)
      IPHI = INT(PHIRND) + 1
      IF (IPHI .EQ. 1) RNDPHI = (45.0 * PI) / 180.0
      IF (IPHI .EQ. 2) RNDPHI = (135.0 * PI) / 180.0
      IF (IPHI .EQ. 3) RNDPHI = (-135.0 * PI) / 180.0
      IF (IPHI .EQ. 4) RNDPHI = (-45.0 * PI) / 180.0
      RETURN
      END
C
      SUBROUTINE DFT(NM1,XIN,XOUT)
C
C    THIS SUBROUTINE COMPUTES THE DISCRETE FOURIER TRANSFORM OF
C    A COMPLEX DATA SET OF N (= NM1+1) POINTS STORED IN THE ARRAY XIN
C    THE RESULT IS STORED IN THE COMPLEX ARRAY XOUT
C
      COMPLEX XIN(0:NM1), XOUT(0:NM1), W, WM
```

```
      N = NM1 + 1
      PI = 4.0*ATAN(1.0)
      EN = N
      NM2 = NM1 - 1
      IF (NM1 .EQ. 0)  THEN
        XOUT(0) = XIN(0)
      ELSE
        BETA = 2.0 * PI / EN
        W = CMPLX(COS(BETA), -SIN(BETA))
        DO 3110  K = 0, NM1
          WM = W**K
          XOUT(K) = XIN(NM1)
          DO 3100  L = NM2, 0, -1
            XOUT(K) = XOUT(K)*WM + XIN(L)
 3100     CONTINUE
 3110   CONTINUE
C
      ENDIF
      RETURN
      END
C
      SUBROUTINE VLINE(J1,JN,XARRAY,B)
C
      REAL XARRAY(0:4096), B(0:4096)
C
C    DRAW VERTICAL LINES
C
      DO 3200  JLINE = J1, JN
        XFROM = XARRAY(JLINE)
        XTO = XFROM
        YFROM = 0.0
        YTO = B(JLINE)
        CALL RLVEC(XFROM,YFROM,XTO,YTO,0000)
 3200 CONTINUE
      RETURN
      END
```

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Thesis
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c.1 Simulation and analysis of a MFQPSK signal transmitted through an acoustic medium.